

FINAL
10-14-92
OCT
1992

Construction of Prototype Lightweight Mirrors

Final Report

Period of Contract: 10 December 1996 to 10 September 1997

Contract Number: H-27657D

Prepared

by

William G. Robinson
Principal Investigator

Electro-Optics, Environment, and Materials Laboratory
Georgia Tech Research Institute
Georgia Institute of Technology
Atlanta, Georgia 30332

Construction of Prototype Lightweight Mirrors

Table of Contents

	<u>Page</u>
1.0 Introduction	1
2.0 Scope of Work	1
3.0 SSD Top-Level Technology Demonstration Requirements	1
4.0 SSD Hardware and Software Requirements	2
5.0 Lightweight Mirror Development	2
5.1 Mirror Design Concepts	2
5.2 Electrical Discharge Machining (EMD) Technique	4
5.3 EDM Tooling	8
5.4 EDM Procedure	10
5.5 EDM Results	14
6.0 Position Sensor	15
6.1 Position Sensor Background	15
6.2 Position Sensor Circuit Die Preparation and Testing	19
7.0 Alternate Sensor Approach	21
7.1 GTRI Packaging Concept	22
7.2 Coil Pair Preparation	22
7.3 Flex Circuit Development	23
7.4 Coil Pair Packaging Concept	24
7.5 Adhesive Selection	29
7.6 Fabrication of Coil Assemblies	31
8.0 Conclusions	32
9.0 Recommendations	32
10.0 Acknowledgments	33
Appendix A: Statement of Work	A-1
Appendix B: SSD Project Plan, Revision 2	B-1
Appendix C: Specifications of Model SM-150B EDM Equipment	C-1

Construction of Prototype Lightweight Mirrors

1.0 Introduction.

This final report describes the work performed by Georgia Tech Research Institute during the period of 10 Dec 1996 to 10 Sep 1997, under Contract No. H-27657D. This contract and the work described was in support of a Seven Segment Demonstrator (SSD) and demonstration of a different technology for construction of lightweight mirrors. The SSD concept was developed by a team. The team involved personnel from NASA Marshall Space Flight Center (MSFC), Naval Air Warfare Center-Weapons Division (NAWC-WPNS), SY Technologies (SYT), Blue Line Engineering (BLE), and Georgia Tech Research Institute (GTRI). The Program Manager for the effort was Mr. E. (Sandy) Montgomery at MSFC.

The objectives of the SSD were to demonstrate functionality and performance of a seven segment prototype array of hexagonal mirrors and supporting electromechanical components which address design issues critical to space optics deployed in large space based telescopes for astronomy and for optics used in spaced based optical communications systems. The SSD was intended to demonstrate technologies which can support the following capabilities;

- Transportation in dense packaging to existing launcher payload envelopes, then deployable on orbit to form space telescope with large aperture.
- Provide very large (>10 meters) primary reflectors of low mass and cost.
- Demonstrate the capability to form a segmented primary or quaternary mirror into a quasi-continuous surface with individual subapertures phased so that near diffraction limited imaging in the visible wavelength region is achieved.
- Continuous compensation of optical wavefront due to perturbations caused by imperfections, natural disturbances, and equipment induced vibrations/deflections to provide near diffraction limited imaging performance in the visible wavelength region.
- Demonstrate the feasibility of fabricating such systems with reduced mass and cost compared to past approaches.

While the SSD could not be expected to satisfy all of the above capabilities, the intent was to start identifying and understanding new technologies that might be applicable to these goals.

2.0 Scope of Work.

The original statement of work for this contract is shown in Appendix A. The work completed on this contract was intended to support basic technology development necessary for the construction of large lightweight mirrors in space and for satellite-to-satellite optical communication systems. Most of the tasks in the statement of work were completed. Several tasks were deleted, modified, or added to meet the technology, schedule, and cost goals of the project. Changes in the scope of work were made in consultation with the COTR (E. Montgomery) in an effort to meet the technical goals of the SSD, schedule constraints presented by the program, and cost limitations of this contract.

3.0 SSD Top-Level Technology Demonstration Requirements.

The following list of top-level technology demonstration requirements were taken from the Seven Segment Demonstrator Project Plan, Revision 2;

The goal of the SSC is to demonstrate:

- Phase locking of a segmented mirror surface.
- Compact (miniaturized) phase loop controller capable of continuous phasing mirrors at a bandwidth in excess of 300 Hz.

- Compact (miniaturized) phase loop controller architecture expandable to many more segments and a tip/tilt control loop for full aperture wavefront correction.
- Miniaturized, high accuracy, high dynamic range edge sensors.
- Miniaturized, high accuracy, high dynamic range, moderate bandwidth, lightweight actuators.
- Very lightweight mirror segments.
- Simple, reliable, robust construction and deployment methods and mechanisms.
- Stiff cluster baseplates for support of segmented mirror arrays.

The SSD component developments were treated as a precursor to constructing a much larger curved aperture made up of many more segments.

4.0 SSD Hardware and Software Requirements.

The guidelines and assumptions developed to serve as hardware and software requirements for the SSD were documented in the Seven Segment Demonstrator Project Plan, Revision 2. These requirements are included in this report in Appendix B.

5.0 Lightweight Mirror Development.

As indicated in the Introduction, the primary goal of the work performed under this contract was to support the development of the SSD. The SSD was intended to be a prototype table-top system that could demonstrate lightweight segmented mirror technologies. The SSD concept included the following three subassemblies; (1) seven segment mirror assembly, (2) mirror control/interface electronics, and (3) system control computer. The work completed in this contract supported development of components for the seven segment mirror assembly.

The mirror assembly concept includes seven lightweight mirrors. Each of the seven mirrors are coupled mechanically to a stiff baseplate using voice-coil type actuators. The edge of each mirror is "electronically coupled" to its neighbors through magnetic position sensors. The system control computer, using specially developed servo/position algorithms, controls the tilt and piston of the mirrors causing them to form a single plane surface.

Two of the team members, Blue Line Engineering (BLE) and Georgia Tech Research Institute (GTRI) were tasked with construction of lightweight mirror substrates using two different techniques. The goal of this development was to fabricate mirrors which were optically and physically identical, using two different approaches. A common goal was to produce mirror substrates that were as stress free as possible, lightweight, and cost effective to manufacture. Both mirror substrate concepts used silicon as the material of choice.

5.1 Mirror Design Concept.

The BLE mirrors consist of a solid thin face-sheet and back-sheet with multiple layers of silicon "snow-flakes" sandwiched between the face-sheet and back-sheet to provide stiffness at minimum added weight. It was intended that the silicon layers would be molecularly bonded to each other to provide essentially a structurally stiff substrate. The lightweighted "snow-flake" layers were produced in batch etching processes similar to processes used in the semiconductor industry. The BLE mirror design is shown in Figure 5.1-1.

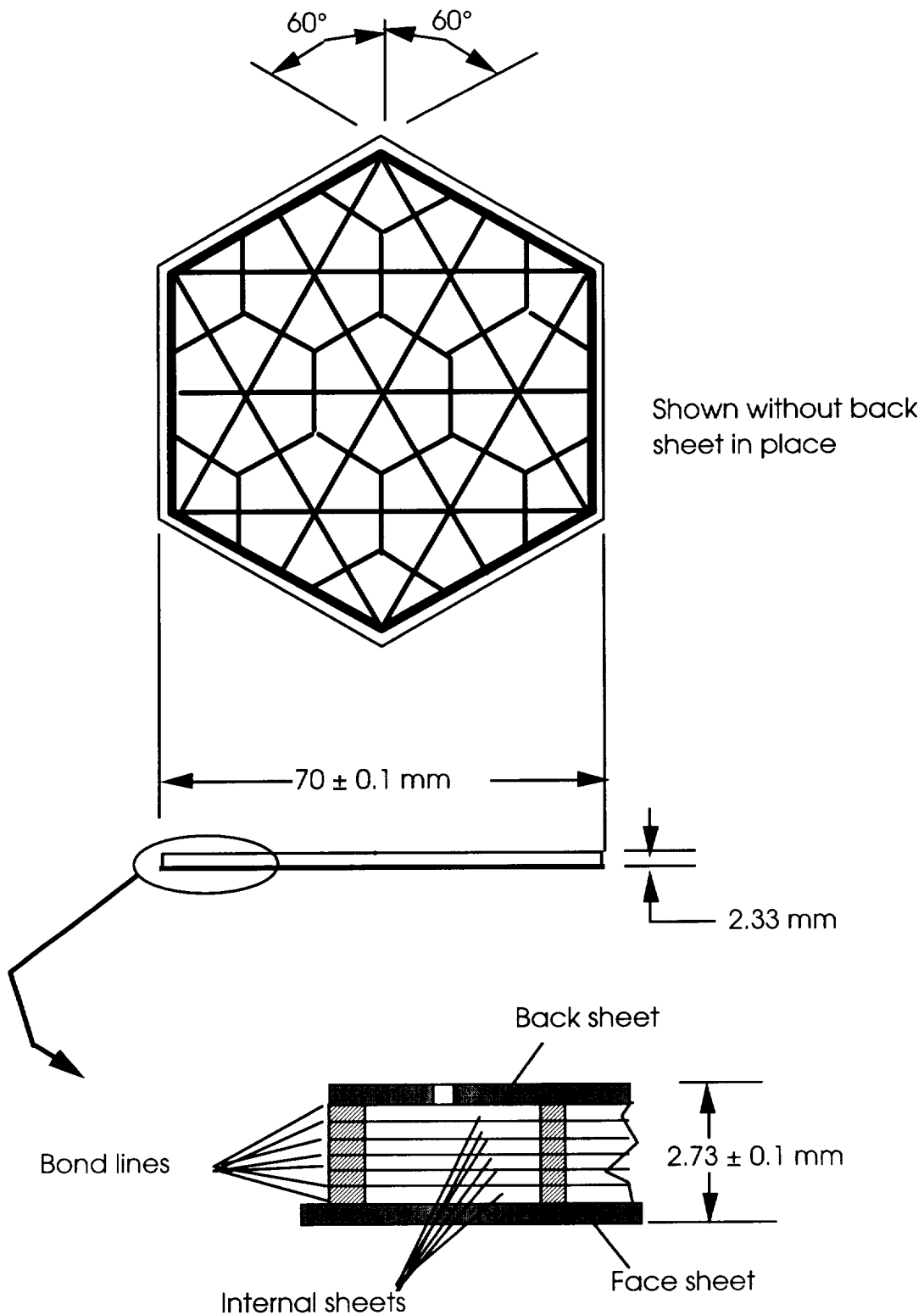


Figure 5.1-1 Lightweight mirror design proposed by Blue Line Engineering.

The GTRI mirror design consists of a solid substrate with cavities machined into one surface and a thin solid (except for small holes) back-sheet which is molecularly bonded (or “glued”) to the main substrate. The Electrical Discharge Machining (EDM) process was used to machine cavities into the solid substrate in an attempt to produce a lightweight structure that is stress free. The GTRI mirror design is shown in Figure 5.1-2.

5.2 Electrical Discharge Machining (EDM) Technique.

Electrical discharge machining is a process that utilizes electrical discharges to remove material from a substrate or workpiece. The surface being machined is bombarded with high intensity electrical energy pulses in the form of discharge produced plasma volumes. These intense discharges remove material from the substrate in a gradual process. Normally this machining technique is used with metal substrates, but for this project crystalline silicon is used as the substrate.

To accomplish the machining operation, a machine tool (electrode) is required to maintain the appropriate electrode-to-substrate relationship and discharge pattern. A power supply is required to produce the electrical discharges, a dielectric oil is required between the electrode and substrate, and a control system is needed to control the machining process. Figure 5.2-1 shows schematically the various parts of the EDM system.

The electrical discharges are the result of a DC potential, provided by the power supply, applied across the gap between the electrode and the substrate. As the electrode is moved toward the substrate, an electrode-substrate distance is reached where the electric field ionizes the dielectric fluid and a discharge occurs. The high energy discharge produces vaporization, melting, and an acoustical shock that dislodges a minute particle of the substrate from the workpiece, leaving a small crater. The dislodged particle or chip is then solidified and washed away by the dielectric fluid. Although the chip and the crater produced by one discharge is extremely small, energy pulses can be delivered to the substrate at a rate in excess of 200, 000 per second to make the rate of material removal significant. This process is illustrated in Figure 5.2-2.

Electrical discharge machining differs from conventional machining in two important respects. In EDM only electrically conductive materials can be machined, and the cut by EDM is slightly larger than the electrode (cutting tool). This extra material removal is referred to as overcut and is a result of the gap maintained by between the electrode and the substrate. The gap is maintained because the electrical discharge always occurs where the field strength is maximum and in this case that is where the gap is smallest.

For a constant electrode/substrate position, machining will continue until a uniform gap occurs at all points between the electrode and the substrate. When the gap is constant, the electrode is moved closer to the substrate and the machining process continues. Feeding the electrode into the substrate is controlled by electrical feedback from the cutting gap. The electrode never comes into contact with the substrate. A reference voltage is established in the power supply and gap voltage is compared to the reference voltage. The electronic servo controller positions the electrode relative to the substrate by controlling a valve that controls the position of a hydraulic cylinder, which in turn positions the electrode.

The controllable factors in conventional machining are present in EDM. These factors are (1) the rate at which material is removed, (2) the finish on the substrate, (3) accuracy, and (4) the efficiency of the operation. In EDM, these factors are controlled by discharge current, discharge frequency, and the electrode feed system. Controls on the power supply permit regulation of the energy contained in the discharges. Both the total energy available for material removal (represented by total discharge current) and the number of pulses per second (frequency) are controllable.

To help provide a controlled field environment between the electrode and substrate, a dielectric fluid is used. To accurately control the EDM process, the dielectric fluid must initially act as an insulator and

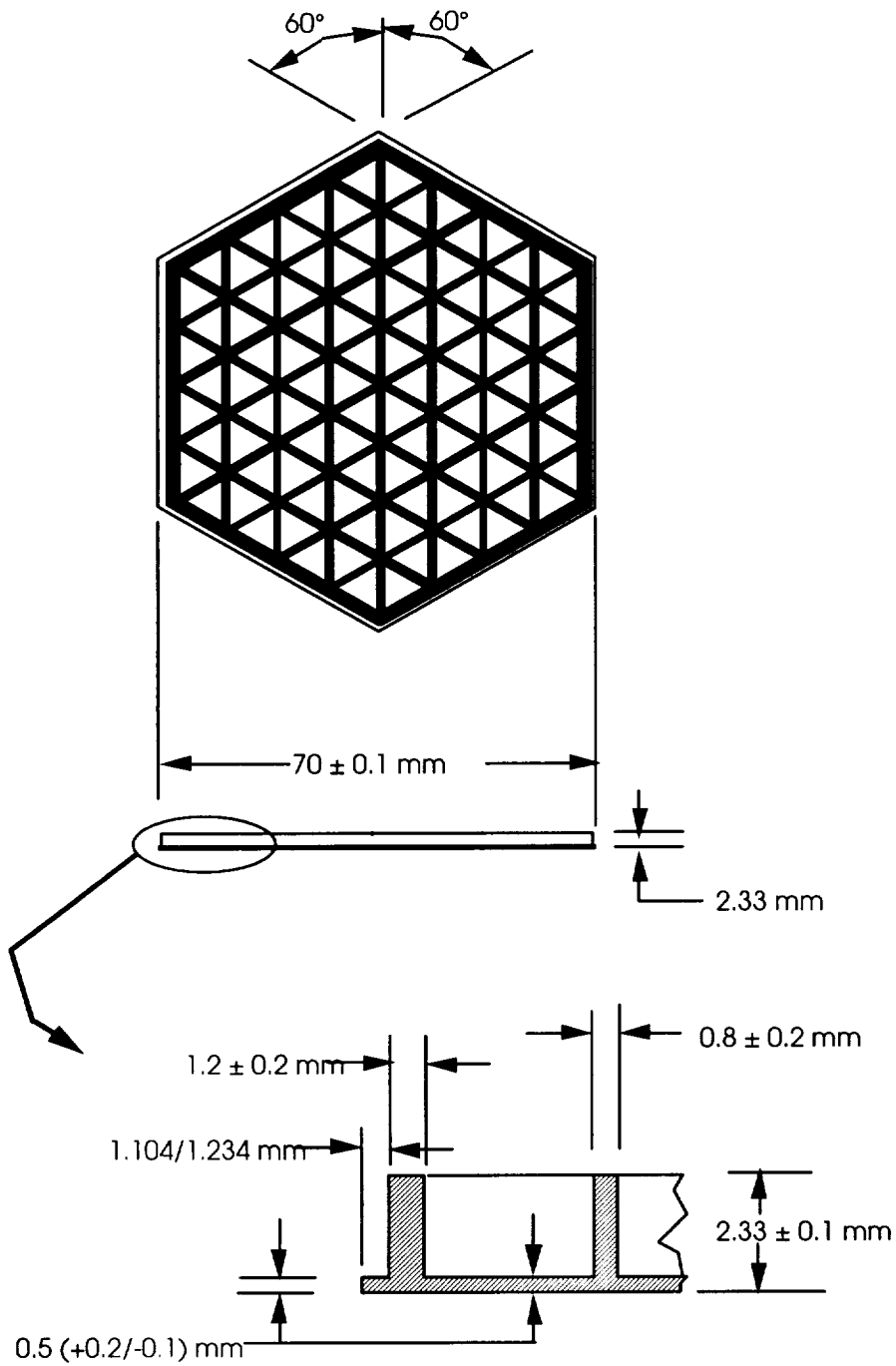


Figure 5.1-2 Lightweight mirror design proposed by Georgia Tech Research Institute

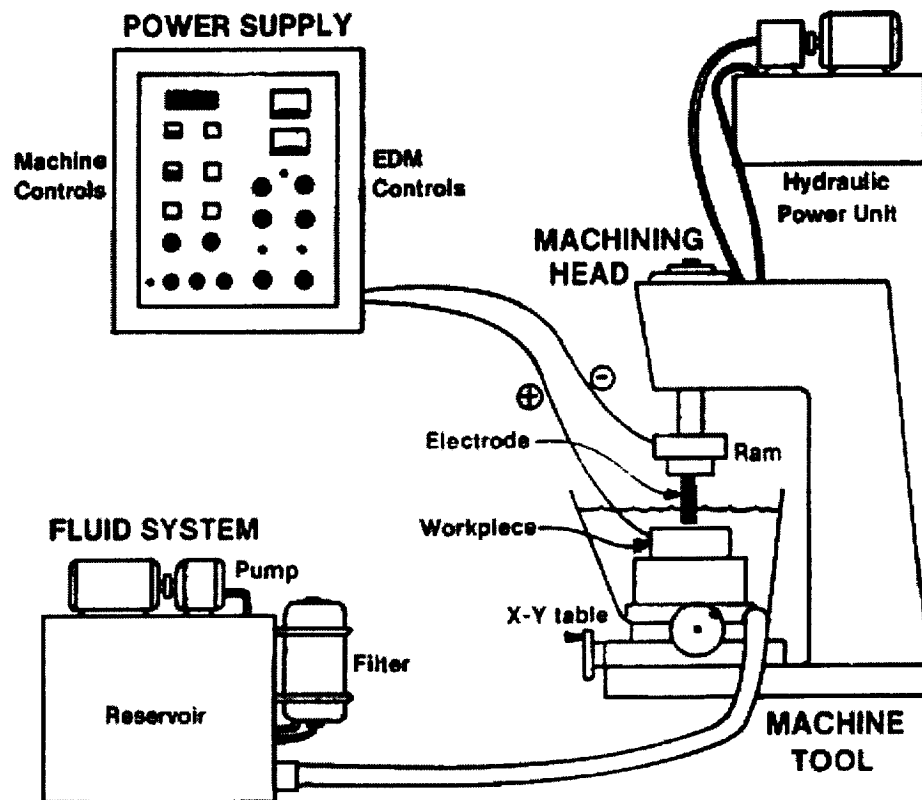


Figure 5.2-1 Schematic representation of EDM equipment.

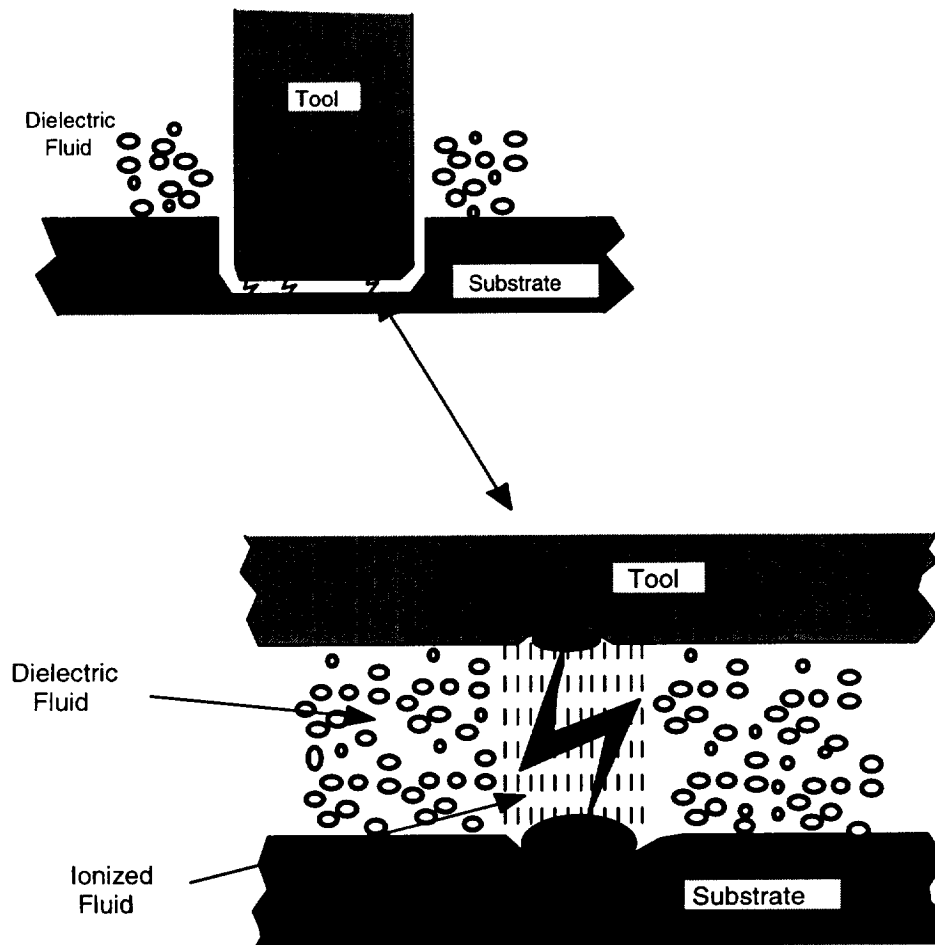


Figure 5.2-2 Illustration of EDM process.

then ionize when a specific field strength is reached, thus allowing current to flow between the electrode and substrate. To be effective, the dielectric must breakdown quickly to insure a discharge with every voltage pulse created by the power supply, and must de-ionize quickly to prevent multiple discharges in the same area. The fluid further serves to solidify the molten particles and provides a washing action to remove the particles from the gap. It also helps to cool the electrode and substrate and maintain a constant gap temperature. Most EDM dielectric fluids are petroleum base, low viscosity oils with additives to enhance cutting speed and raise the flash point.

Adequate flushing of the gap is important to clear the cutting area of residue. When too much residue is left in the gap, the electrical discharges may be transferred through the gap by the particles. This "stepping stone" effect reduces the efficiency of the discharge. Under this condition, the gap will break down at a lower voltage and the magnitude of the discharges will be reduced. This lessening of discharge magnitude reduces material removal rate and permits build up of carbon on the electrode. A carbon build up on the electrode reduces the efficiency of the servo sensing unit, which further reduces the cutting efficiency.

The EDM equipment used for fabrication under this contract was made by Hansvedt Engineering Inc. and is Model SM-150B. The specifications and a picture for this unit are given in Appendix C.

5.3 EDM Procedures.

As stated earlier, the EDM process is normally used with a metal substrate. In this project, the EDM substrate is crystalline silicon. Two types of silicon substrates were used (both were amorphous silicon) in the experimental development of the EDM procedures. P-type silicon wafers with a resistivity of 0.008-0.020 ohm-cm and N-type silicon wafers with a resistivity less than 1 ohm-cm were used. The silicon wafers were purchased as 100 mm diameter disks, 2.33 mm thick. The disks were purchased with both sides polished to a mirror finish. The supplier of the silicon wafers was asked to provide the same polish and flatness specification as is standard for the semi-conductor processing industry.

For the EDM process to work, both the tool electrode and the substrate must be connected to the power source. The normal electrical configuration is for the tool to be connected to the negative (-) output of the power source and the substrate to be connected to the positive (+) output of the power source. To provide a uniform electrical connection to the silicon substrate, the substrate was attached to an aluminum rod with a mixture of silver conductive paint and Ducco brand cement. The paint used was SPI #5002 High Purity Silver Paint for scanning electron microscopy sample preparation. After applying the paint/cement mixture to the end of the aluminum rod, the silicon wafer was placed onto the end of the rod and a weight was placed on top of the silicon wafer. This assembly is shown in Figure 5.3-1. After the paint dried, the assembly was placed onto the EDM equipment and the aluminum rod was connected to the (+) output of the power source.

In some of the original substrate assemblies, air pockets got between the substrate and aluminum rod. These air spaces would result in electrical discharges between the substrate and the aluminum rod, causing the "back" of the wafer to be machined in those areas where air existed. It is believed that this is due to the relatively high resistivity of the silicon relative to the silver paint and aluminum rod, thus allowing locally high field strengths in air causing the air to ionize and a discharge to occur. This was later minimized by placing the assembly under vacuum prior to curing.

Another problem that occurred in the earlier stages of the project was that the EDM dielectric fluid would dissolve the conductive paint/cement mixture and wick into the area between the substrate and the aluminum rod. This wicking action reduced the mechanical bond strength between the substrate and the aluminum rod and the substrate could be pulled off of the aluminum rod by the tool or uneven machining would occur at the surface of the substrate. The wicking problem was solved by

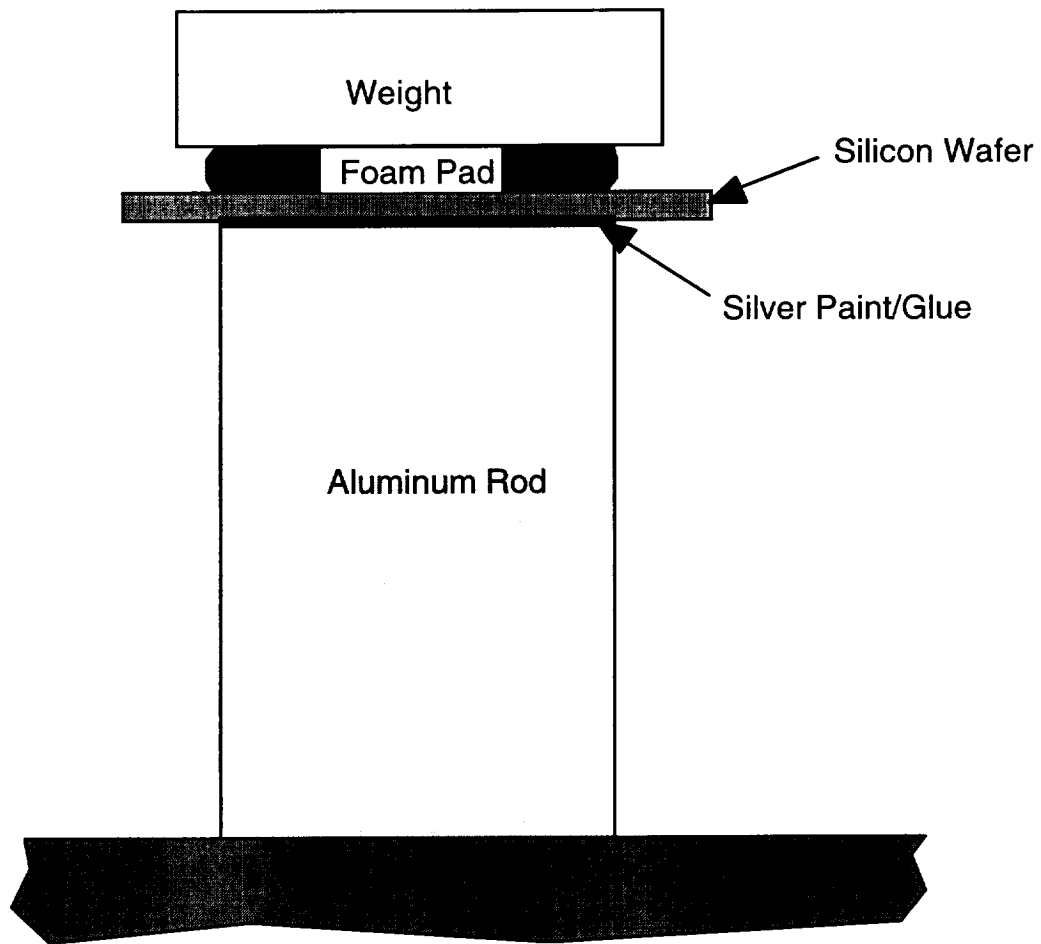


Figure 5.3-1 Preparation of substrate assembly.

using a sealant around the outside edge of the substrate/aluminum rod. The sealant used was clear GE Silicone II as shown in Figure 5.3-2.

Once the substrate assembly was put in place on the X-Y table of the EDM machine, the tool was aligned so that the tool was parallel to the substrate and the tool motion was perpendicular to the substrate. Then the tool and substrate were immersed in dielectric fluid and the machining process was started.

Initial machining attempts ended in failure when the tool “short circuited” to the substrate and the servo controller sensed that the tool was touching the substrate and pulled the tool away from the substrate. When a “short circuit” occurred, a molten glob of material would cause a bridge between the substrate and the tool. The bridge would cool and solidify, creating a solid physical connection between the substrate and tool. When the tool was pulled back from the substrate, the substrate was either pulled off of the aluminum rod or what usually occurred was that the substrate was broken. Figure 5.3-3 shows a substrate broken as a result of one of these “short circuit” occurrences.

It was theorized that the “short circuits” between substrate and tool were caused by small pieces of conductive substrate debris being removed in the machining process or conductive contaminants in the dielectric fluid. An attempt was made to solve this potential problem by (1) redesigning the tool to allow better flushing of the substrate, (2) addition of a higher flow rate pump, (3) redesign of the fluid flushing jets to provide a broad flow sheet across the substrate instead of local nozzles, (4) replacement of the fluid filter, (5) and replacement of the dielectric fluid.

In order to minimize the probability of “short circuits” the amount of current supplied to the substrate was lowered dramatically. The amount of average current available can be controlled by the duty cycle of the discharge and/or by the frequency of the energy pulses. Several different combinations were tried in an attempt to minimize the occurrence of short circuits. Decreasing the average current, decreases the material removal rate and dramatically increased the time it would have taken to produce a machined substrate.

5.4 EDM Tooling.

Little knowledge or experience existed in determining the best material for the EDM tool in this application, because a silicon substrate is not normally used. Based on a review of tool materials for other applications, oxygen-free copper was chosen as the material for the tool. Oxygen-free copper machines easily, provides a good finish, has high conductivity, is readily available, relatively inexpensive, and works well in other EDM applications.

The tool represents an inverse volume to the volume that is to be removed. For ease of fabrication, the tool was built in several pieces and assembled into one piece. The complete tool is shown in Figure 5.4-1. The main body of the tool provides for removal of the substrate material to create the pockets in the substrate and skirt around the perimeter of the tool created a shelf or indented area around the perimeter of the substrate and defined the outside edge of the finished substrate.

One of the problems with the design of this tool is that it is very difficult to get good fluid flow between the tool and substrate without raising the tool significantly above the substrate. Having to stop the machining operation and raise the tool to properly flush the substrate dramatically increased the time it took to machine a substrate. To help alleviate this problem, a new tool design was required. Unfortunately, the contract did not have sufficient time or money to design and fabricate an improved tool.

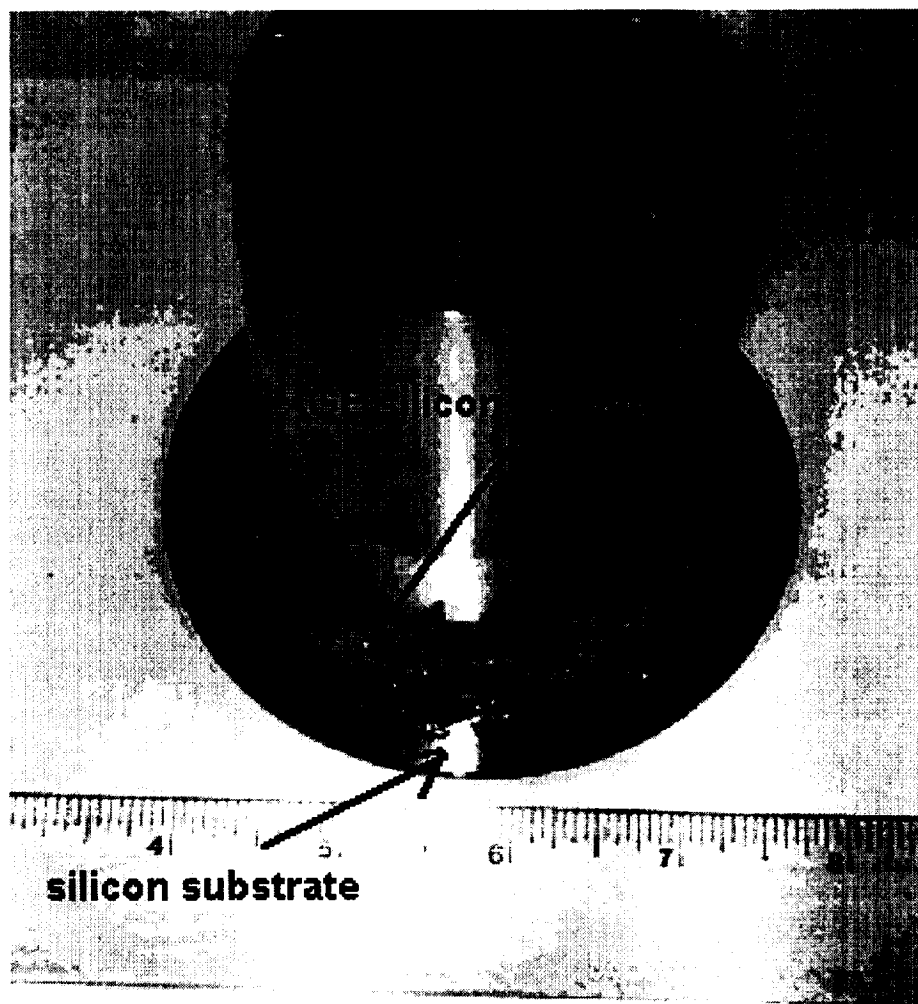


Figure 5.3-2 GE Silicone II used as a sealant from dielectric fluid.

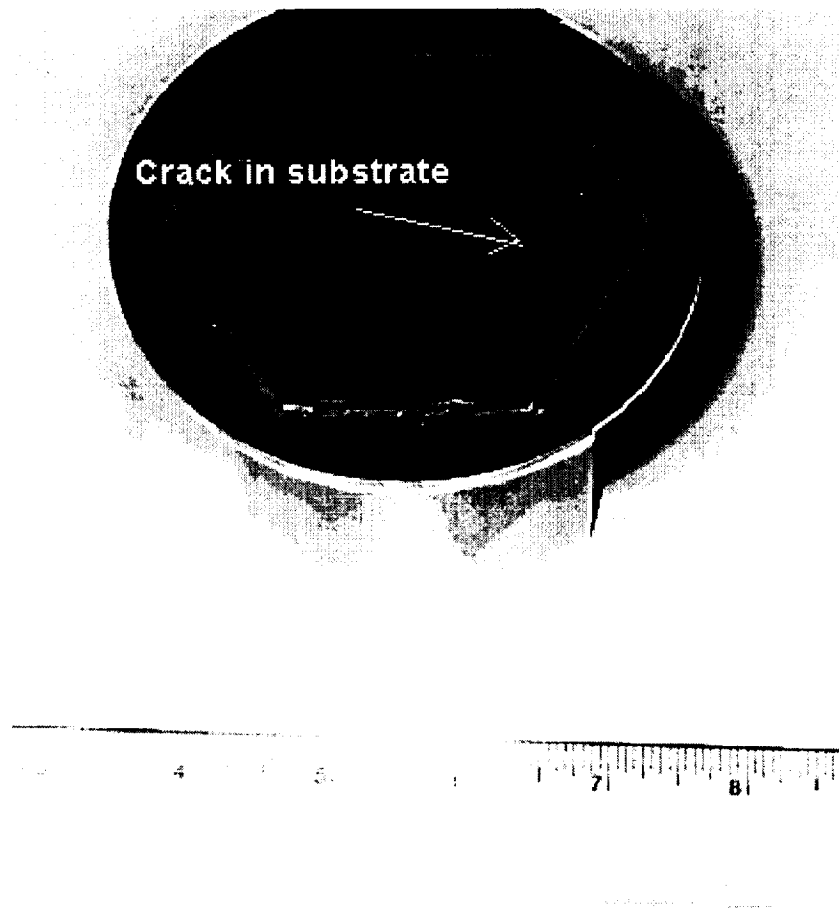


Figure 5.3-3 Broken substrate resulting from tool withdrawal due to "short circuit" between tool and substrate.

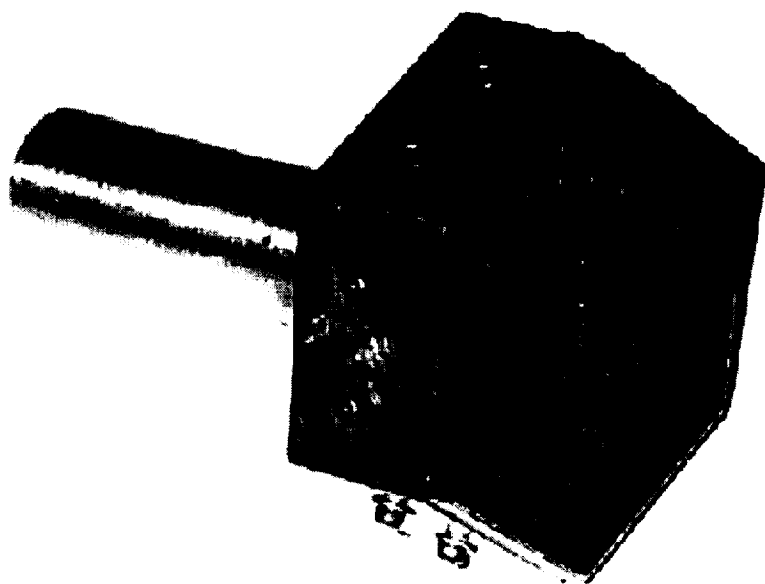


Figure 5.5-1 Partially complete lightweight mirror substrate produced with EDM technique.

5.5 EDM Results.

While the development of the EDM technique showed promise for fabrication of light weight mirrors and other structures, many small technical problems prevented a suitable mirror substrate from being completed during this contract period. The best effort toward a mirror substrate is shown in Figure 5.5-1. The machining on this substrate took 54 hours due to reduced machining current and frequent raising of the tool for flushing. Even with these precautions, the machining ended in failure due to a "short circuit" which resulted in the substrate cracking when the tool was withdrawn.

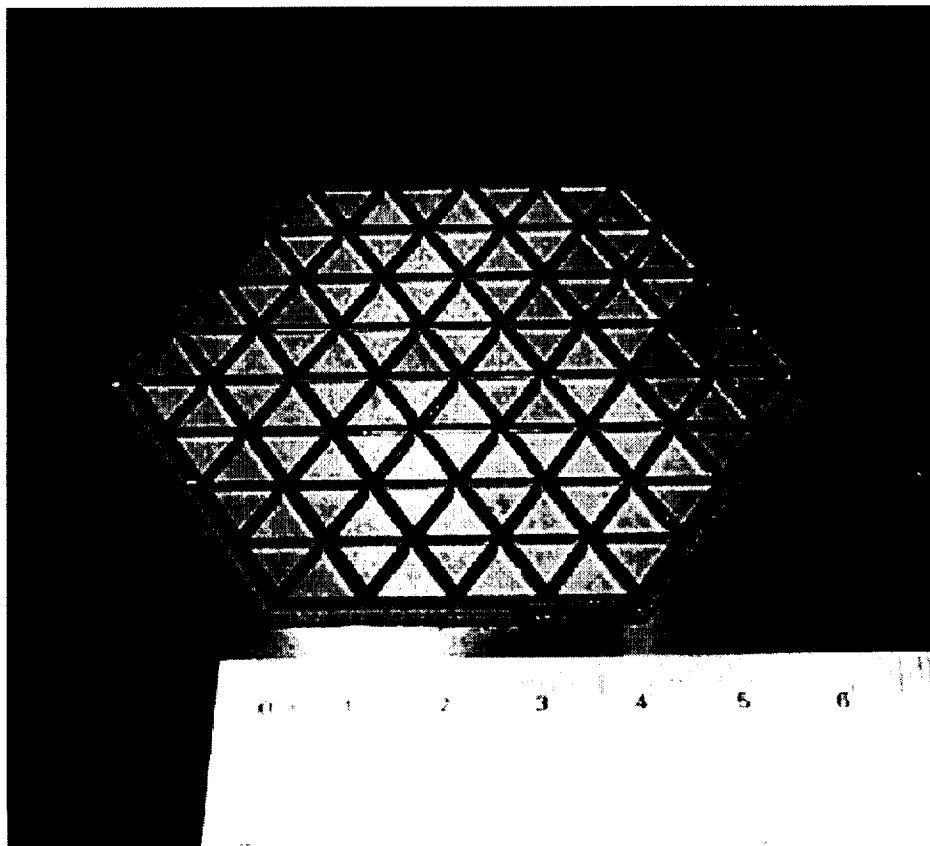


Figure 5.4-1 Partially completed lightweight mirror substrate produced with EDM technique.

6.0 Position Sensors

The mirrors in the SSD are used to form a quasi continuous surface, with minimal wavefront deviation. To make the seven smaller segments look like one large mirror, the edges of the segments must match in tilt and piston (displacement). The relative position of the edges of the hexagonal mirrors segments are measured and this relative position is used as feedback for the servo control system. The edge sensors must have the following properties;

- Large positional dynamic range ($\pm 200\text{ }\mu\text{m}$ or larger)
- Good resolution ($<4\text{ nm rms}$ or less)
- Fairly low non-linearity (1% or less of range)
- Good frequency response (10 kHz or higher)

Magnetic position sensor developed by Kaman Aerospace on an Air Force program called PAMELA met the above requirements, but were difficult and expensive to produce in large quantities. The SSD program goal was to develop a magnetic sensor similar to the Kaman sensor, but less expensive.

6.1 Position Sensor Background.

Prior to GTRI joining the SSD development team, BLE and SYT developed a magnetic position sensor concept to meet the requirements listed above. The original SSD edge sensor design included two integrated circuit die, each one mounted on adjacent edges of a mirror as shown in Figure 6.1-1. As originally envisioned, each edge sensor circuit had the identical layout, but were interconnected differently depending on its use as a passive or active element. Each sensor pair has one passive coil pair and one active coil pair.

The sensor circuit, shown in Figure 6.1-2, contains pads for connection of two coils, drive/oscillator circuitry, and an array of electrical interconnect pads. The sensor circuit was designed by SYT and fabricated by the MOSIS Fabrication Service. The circuits were fabricated with two circuits per die as shown in Figure 6.1-3. A total of 44 die (88 sensor circuits) were purchased by GTRI, under a separate contract, for the SSD. GTRI had the task of dicing the die into two separate die, each containing one sensor circuit. In the original sensor concept, two coils were to be attached to each circuit and the interconnect pads were to be configured using external bond wires and flex circuitry.

The small coils to be used with the circuits were required to have more inductance than is feasible with normal integrated circuit processing techniques so a special process was employed to fabricate the coil pairs. The coils were produced by the North Carolina Micro-machining Center (NCMC), using the LIGA process. The LIGA process is capable of producing miniature nickel coils that have a thickness-to-width ratio of 4 or 5 to 1 with very straight walls. This allowed the small coils to have the inductance necessary for this application. The LIGA coils are shown in Figure 6.1-4. The more traditional way of producing similar coils in the past was by actually winding the coils with special wire on special bobbins. The previous technique was very labor intense, time consuming, and produced low yields due to assembly problems.

In developing the initial sensor concept, SYT had planned to have the coils fabricated by NCMC and the circuit dies fabricated by MOSIS Fabrication Service; then SYT would transfer and bond the coils to the circuit dies to complete the sensor. However, in the design or fabrication of the coils, something went wrong and the coils were produced up-side-down. This meant that the original transfer technique envisioned by SYT would not work and two transfers would be required. This meant a new transfer and bonding scheme would have to be developed.

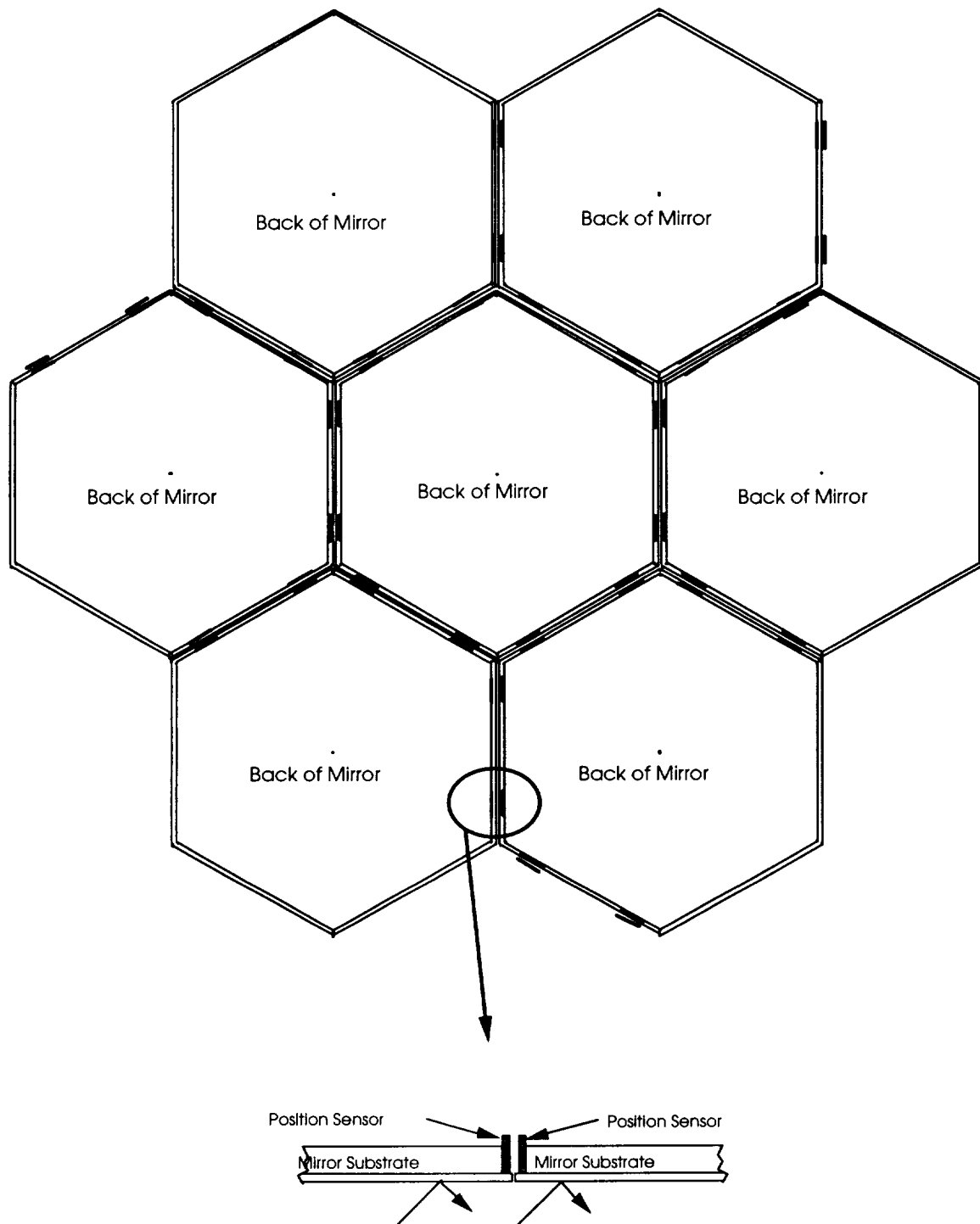


Figure 6.1-1 Position sensor mounting on edges of mirror substrates.

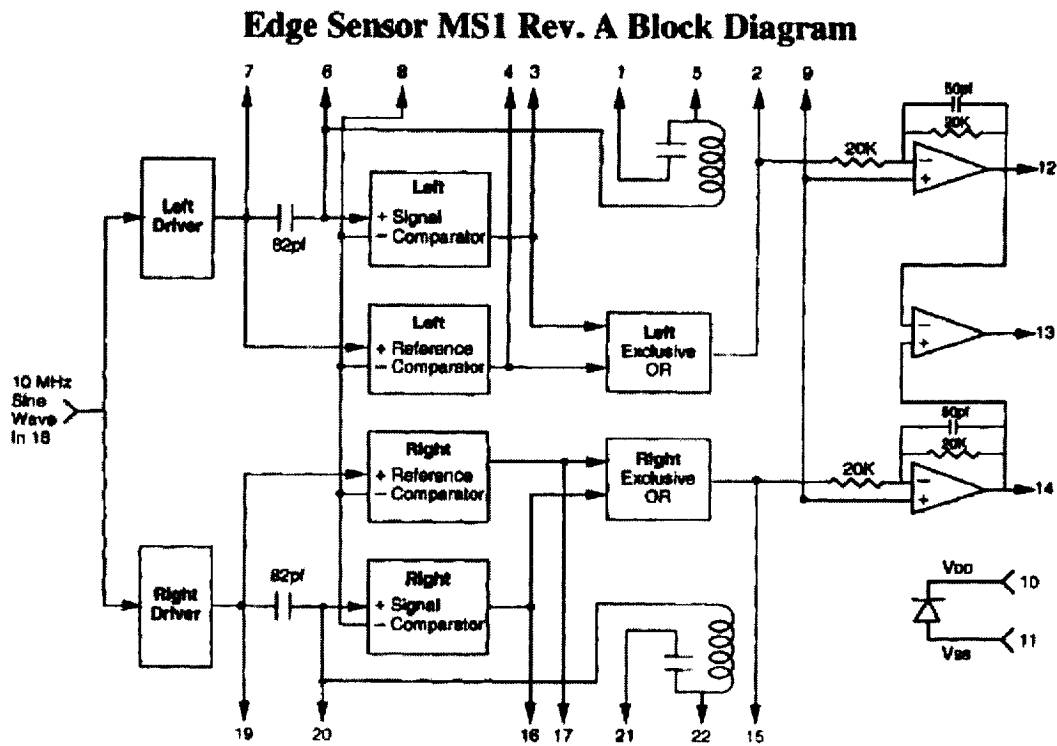


Figure 6.1-2 Sensor circuit schematic (top) and sensor circuit layout (bottom)

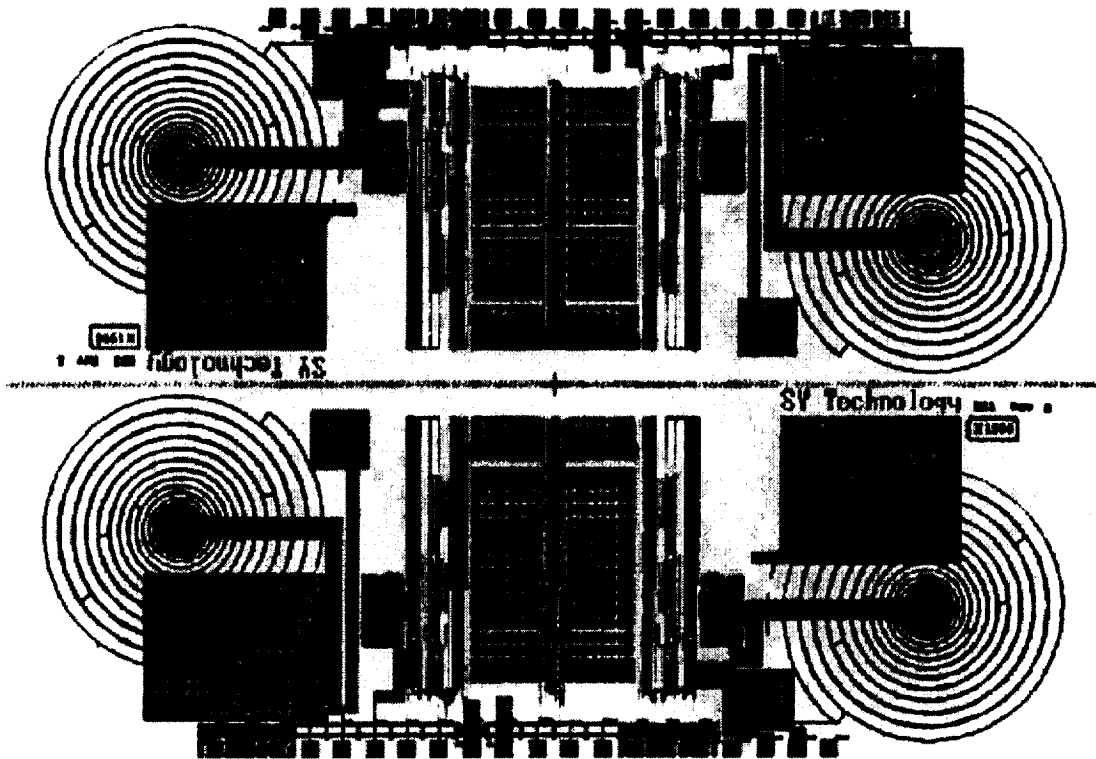


Figure 6.1-3 Sensor circuit as produced by MOSIS Fabrication Service (2 circuits/die)

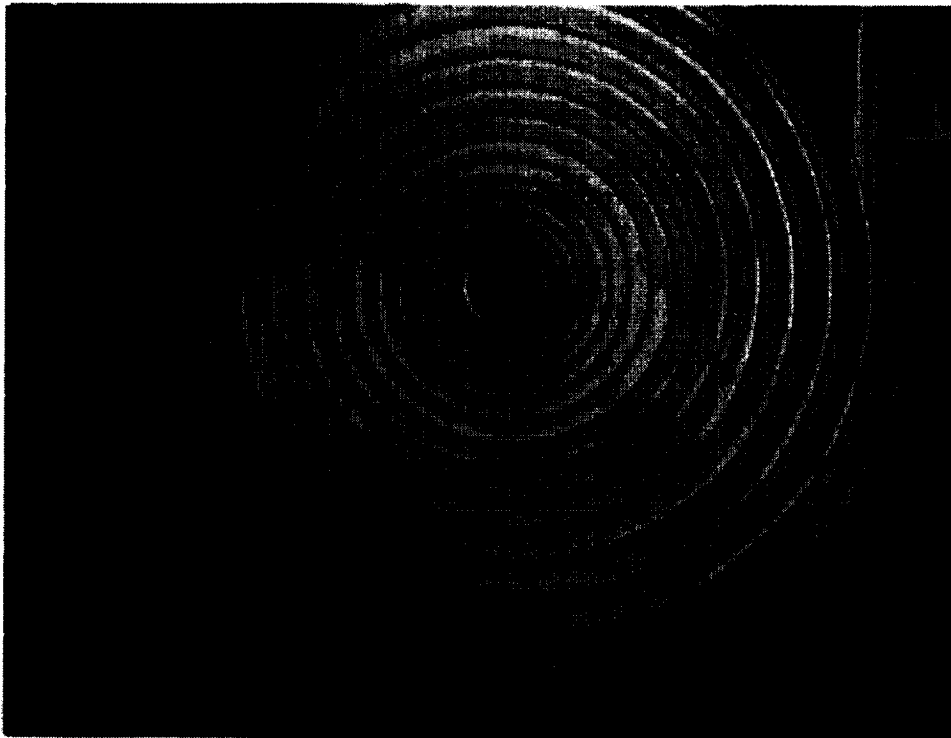


Figure 6.1-4 Nickel coils produced by NCMC using the LIGA process.

6.2 Position Sensor Circuit Die Preparation and Testing.

Prior to making the investment in developing a new transfer scheme and the labor to do the transfers, the team decided it would be appropriate to test the circuits to make sure they worked. Initial testing was done using an IC probe station at GTRI. These tests were inconclusive due to difficulties encountered with the probe station. It was then decided to produce 6 packaged test devices. The circuits, as received from the MOSIS Fabrication Service, had been cut from the original wafer to allow two circuits per standard MOSIS die as shown in Figure 6.2-1. GTRI assembled the test devices by attaching the dual circuit dies to a standard IC package (PGA84M) and then wire bonding from the circuit pads to the package leads. The assembled test devices are shown in Figure 6.2-2. The packaged circuits could then be inserted into a socketed test board to test and characterize the sensor circuits. GTRI sent the packaged sensor circuits to SYT for testing with their test equipment. Testing at SYT indicated that the circuits were not usable.

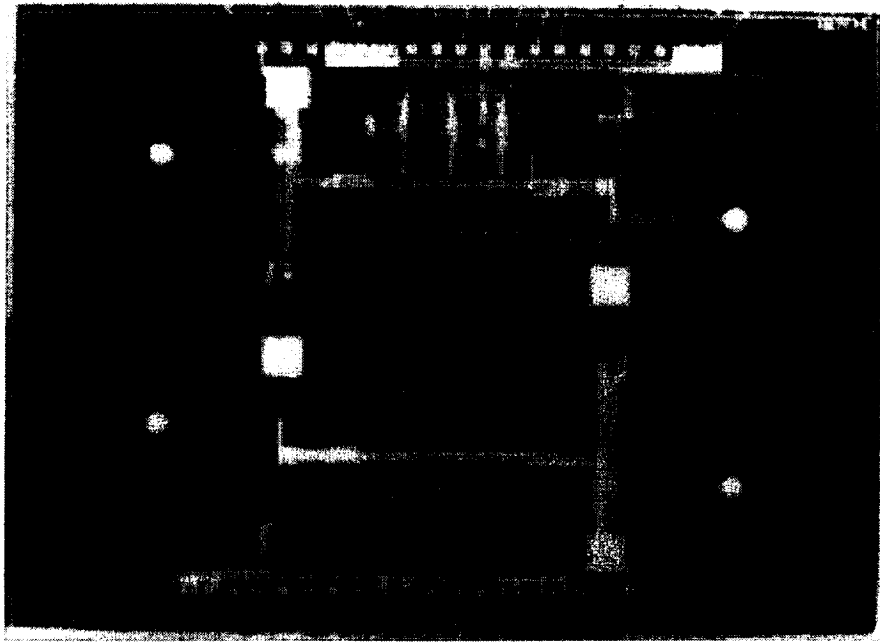


Figure 6.2-1 Test package produced at GTRI showing the two circuits per die.

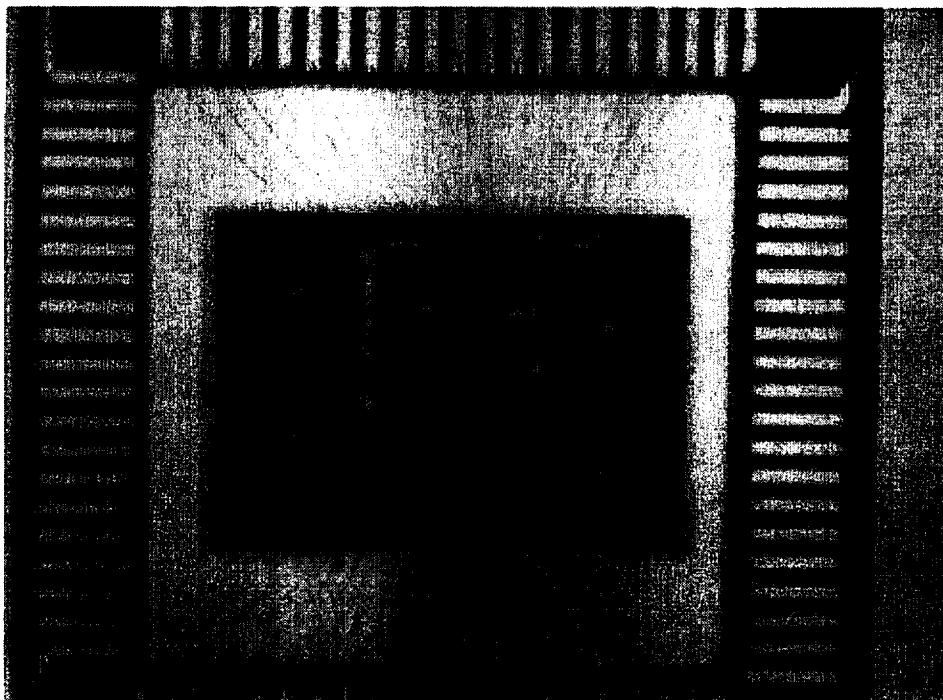


Figure 6.2-2 Test package (PGA84M) showing bond wires from die to package leads.

7.0 Alternate Sensor Approach.

Since the integrated sensor circuits did not work and the coils were up-side-down, the team sought alternate approaches to producing the magnetic position sensors. The most straightforward approach and only real alternative, due to dwindling funds and time, was to produce the sensor circuit in printed wiring board format. The sensor circuits for each active sensor would be mounted off of the mirror on a printed wiring board to better control thermal problems and minimize mirror weight. A flex circuit would be run from the circuit board to coil pairs mounted on the edge of the mirrors. This concept is shown in Figure 7.0-1. Then the only other problem was the coils. Several approaches were investigated; including having coils wound the traditional way, having coils micro-machined from a solid thick film, having them made with a recently developed technique that uses a very thick photo-resist and traditional plating techniques. In the end, it was decided that GTRI would attempt to salvage the original LIGA coils and develop a method of attaching a flex circuit to these coils and BLE would attempt to get some miniature coils hand wound. GTRI accepted the goal of trying to develop a packaging concept that would allow the LIGA coils to be mounted to the edge of the mirrors and allow attachment of a flex circuit to the coils.

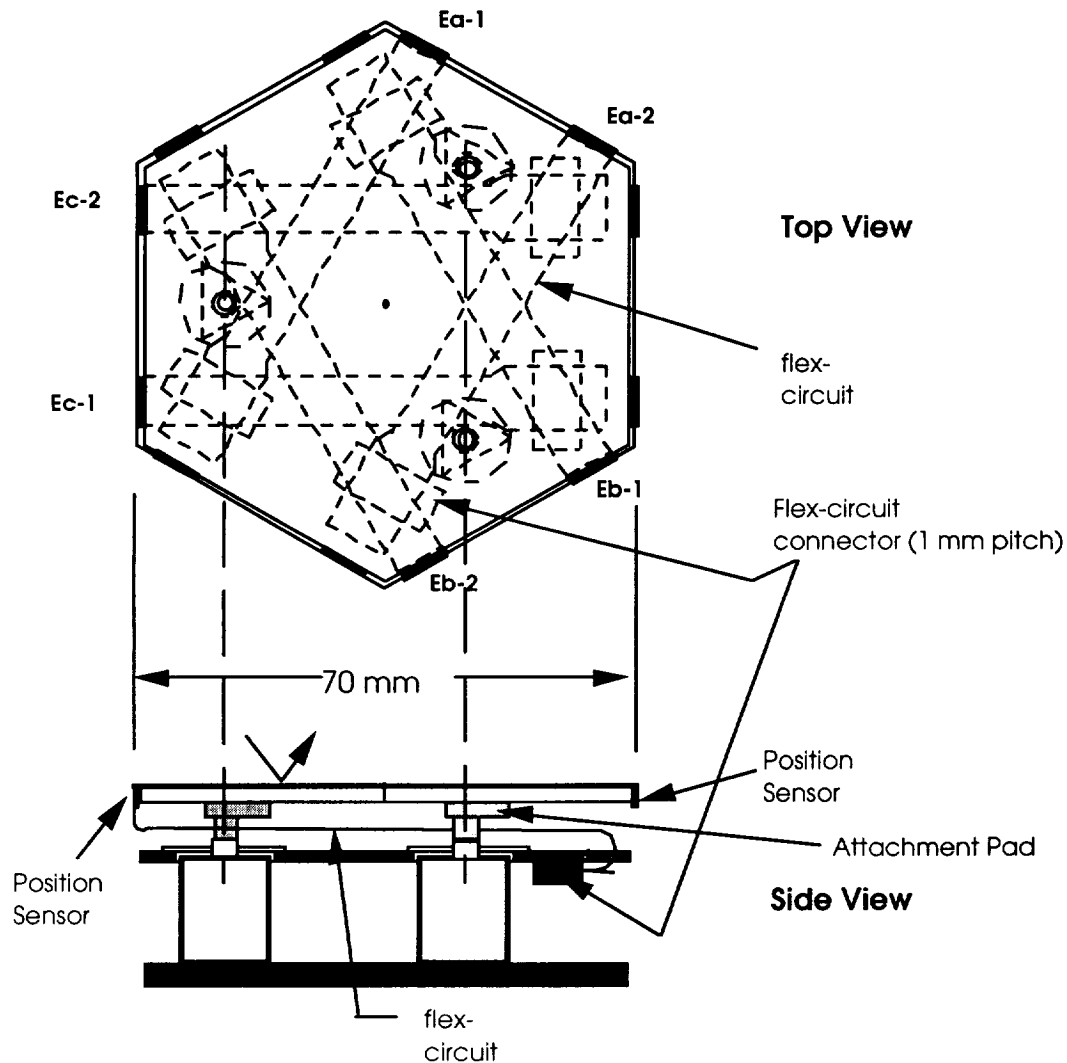


Figure 7.0-1 Alternate packaging concept with coils on mirror edge and sensor circuit on printed wiring board.

7.1 GTRI Packaging Concept.

GTRI's participation in the overall packaging concept for the SSD was initially started under a separate contract in the form of a grant related to the development of wavefront sensor concepts for large space based telescopes and many of the early designs and concepts were developed under that grant. The coil packaging concept finalized in this contract is based, in part, on the earlier work.

Earlier concepts included wire-bonding between circuit pads on silicon to circuit pads on polyimide (flex circuits). For various reasons, these concepts proved to be too labor intense (expensive), too fragile, or required special bonding equipment that was not standard in the industry. GTRI finally settled on the design shown in Figure 7.1-1. This design is simple, robust (does not require fragile wire bonds), and allows a large number of prototype packages to be made fairly quickly using simple fixturing. Details of this packaging scheme are described in the following sections.

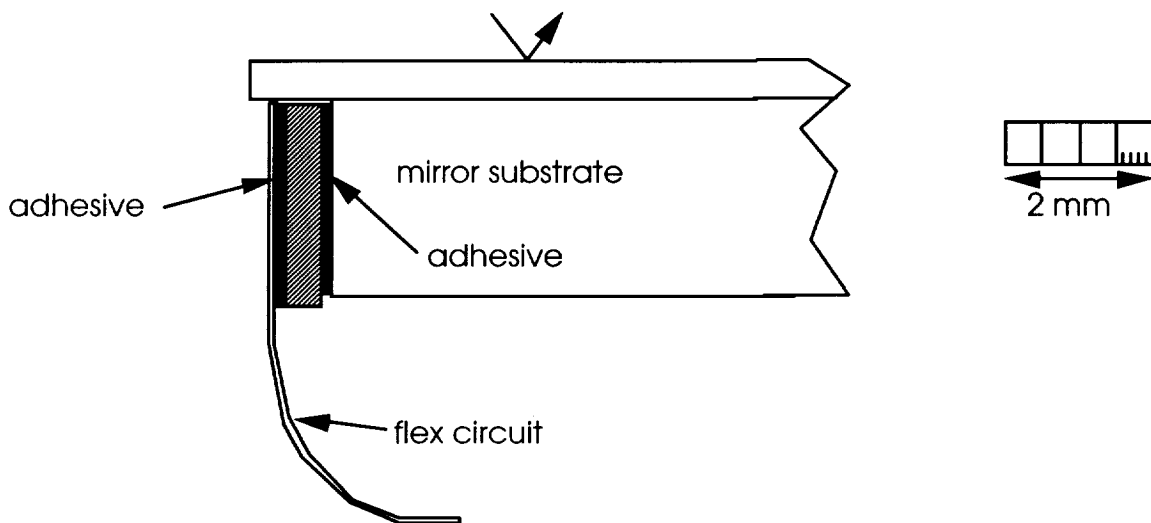


Figure 7.1-1 Coil pair packaging approach

7.2 Coil Pair Preparation.

The LIGA coils were produced on a silicon substrate with sacrificial layers of copper and titanium between the nickel coils and the silicon, as shown in Figure 7.2-1. Also, many coil pairs were produced at the same time on a single substrate. The first task in producing a usable coil pair die, was to dice the substrate into small die; each containing a coil pair. This was done using standard silicon saws used in IC die fabrication at GTRI.

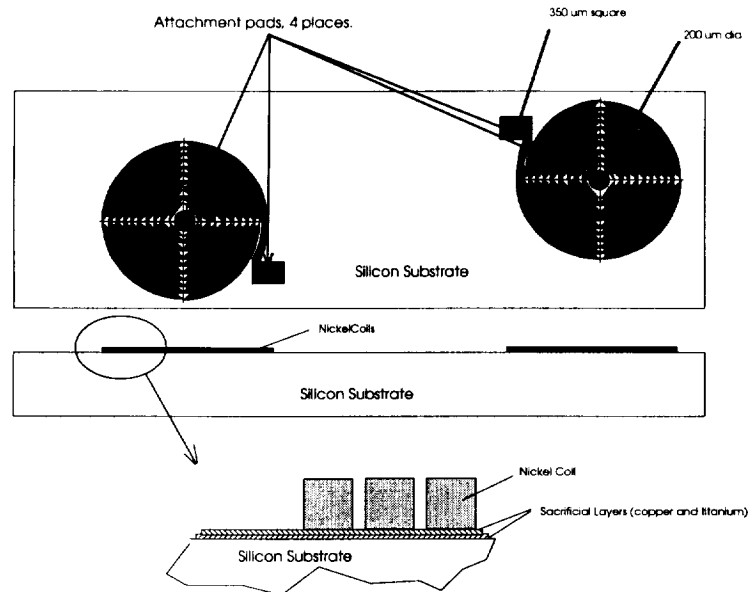


Figure 7.2-1 Sacrificial layers applied during fabrication between nickel coils and silicon substrate.

After dicing the coil wafer into separate coil pair die, the next task was to remove the sacrificial copper and aluminum layers between the coils and the silicon substrate. This sacrificial layer shorted all the coil windings and had to be removed in order for the coil to produce a magnetic field. The procedure was to soak the coil die in a solution of 1 part Ammonium Hydroxide (30% assay), 1 part Hydrogen Peroxide (30% assay), and 6 parts deionized water. The test coil die was soaked for various lengths of time until an optimum was found. The optimum soak time was determined to be in the range of 5-6 hours. The test coil die was tested by interrogating various regions of the die with the x-ray spectrum using an electron microscope at GTRI. After 3 hours of soaking, it was found that some of the sacrificial layers between the coil windings had not been removed. After 6 hours of soaking some portions of the coil were loose from the silicon indicating that the sacrificial layer under the coil had been removed, which was not desirable. In this case it was felt that it was better to error on the side of too much etching, as opposed to running the risk of a shorted coil, so the remaining die were etched for 6 hours to insure a low probability of shorting. After etching of the die to remove the sacrificial layers, the die were rinsed in deionized water to stop the etching, and then air dried.

7.3 Flex-circuit Development.

At the beginning of the project, when the sensor circuit die looked like a viable option, contact was made with Nancy Holloway at NASA Langley Research Center to see if they could fabricate us some flex circuits using a new substrate they had developed called LaRC-SI. LaRC-SI is a polyimide type of material which can be layed down in very thin layers which allows a very flexible membrane. Initially, the flex circuit designs had eight traces, as shown in Figure 7.3-1, to accommodate all of the power and signal connections required to operate the sensor circuit. This flex circuit design and associated packaging scheme was developed by GTRI under a previous contract with NASA MSFC.

After it was determined that the sensor circuit die did not meet our requirements and it was decided to use the coil pair die, the flex circuit was simplified. The flex circuit design for use with the coil pair die is shown in Figure 7.3-2. This circuit required only 4 conductors to allow interconnect with the two

coils on the die. The base insulating material was 0.002" thick LARC-SI, the conductive traces were 200 Angstrom nickel tie-down layer with 1 oz. copper traces over the nickel. The membrane then had a 0.0005" film of LARC-SI over the top of most of the conductive trace area to protect against shorts. To allow the flex circuit to be inserted into a connector, a 0.008"-0.010" thick Mylar stiffener was bonded to one end of the flex circuit with Macktac adhesive. Both sides of this flex circuit is shown in Figure 7.3-3.

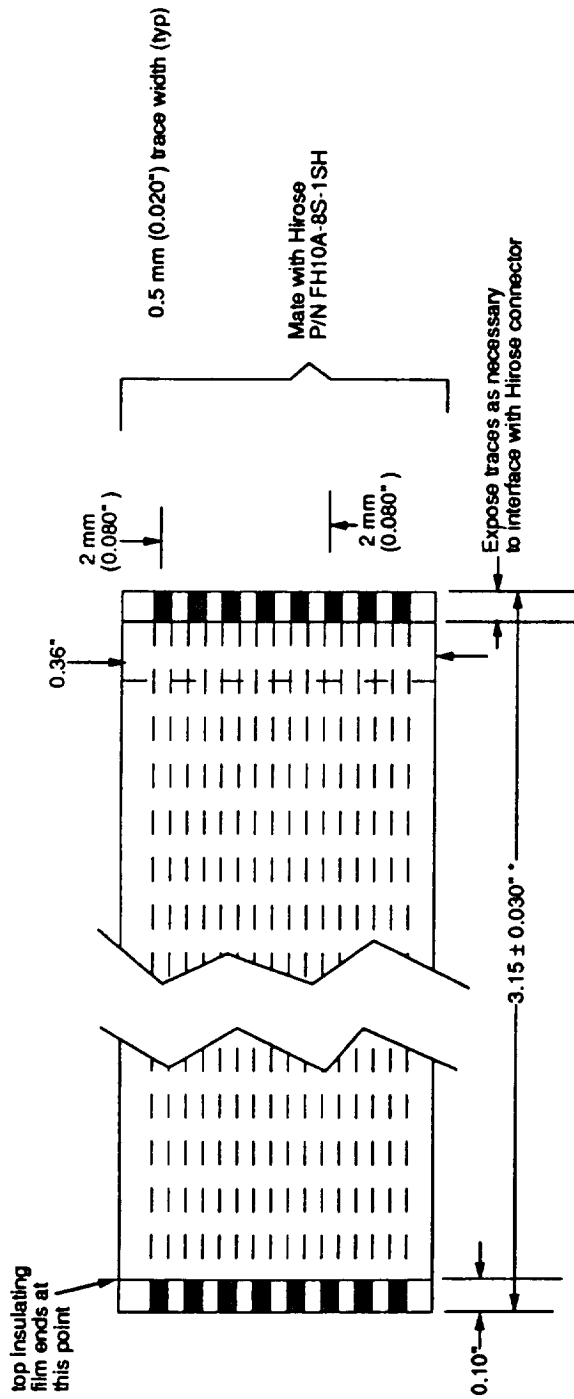
To facilitate connection of the flex circuit to the printed wiring board that held the sensor circuitry in the revised concept, a Hirose flex circuit connector (P/N FH10A-8S-1SH) was chosen. This connector accepts flex circuits with 8 traces on 1 mm center spacing and is attached to the printed wiring board with surface mount techniques. In our design, only four of the eight interconnect locations are used. This interconnect scheme allows a low insertion force, locking, interconnect that is easy to install and use for prototype work that requires fairly high density interconnects using flex circuits.

7.4 Coil Pair Packaging Concept.

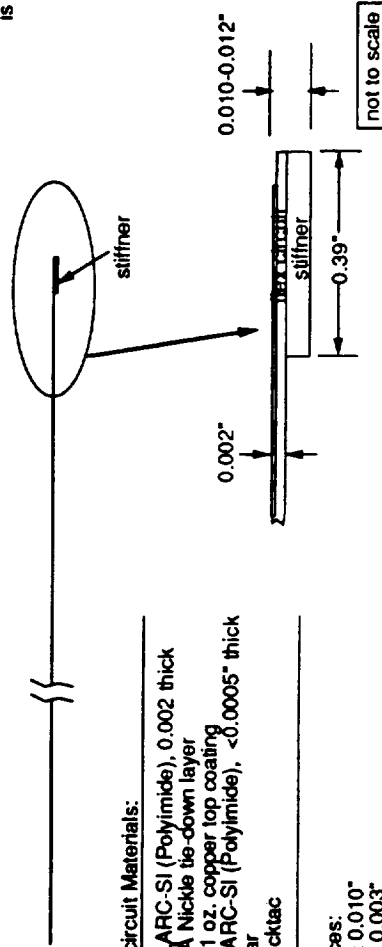
The packaging concept for the coil pairs is shown schematically in Figure 7.4-1. The coil pair packaging consists of a silicon die with two LIGA produced coils, a flex circuit attached to the top of the die/coils with adhesive, and a means of electrically connecting the coils to the conductors of the flex circuits. The electrical connections were made with a conductive silver paint. The following sections describe some of the details of the process. Figures 7.4-2 and 7.4-3 show photographs of the assembly before and after the conductive interconnects are made.

The success of this design depends on being able to precisely locate and drill holes through the polyimide to facilitate an electrical connection between the circuit pads on the silicon die and the copper conductors in the flex circuit. GTRI identified two techniques that would work. One of the techniques used a laser to drill (vaporize) the hole and the other technique used a micro-miniature drill to machine the hole. The laser machining technique was the first technique tried and it worked so well, the mechanical drilling technique was not attempted. The holes in the prototype coil assemblies were drilled by Potomac Photonics, Inc. in Lanham, MD. Greg Behrman and Sidney Wright were our contacts at Potomac Photonics

Flex-Circuit (Design 4)
Specification Control Drawing



Note: (*) Indicates that length dimension is not to scale in this drawing.



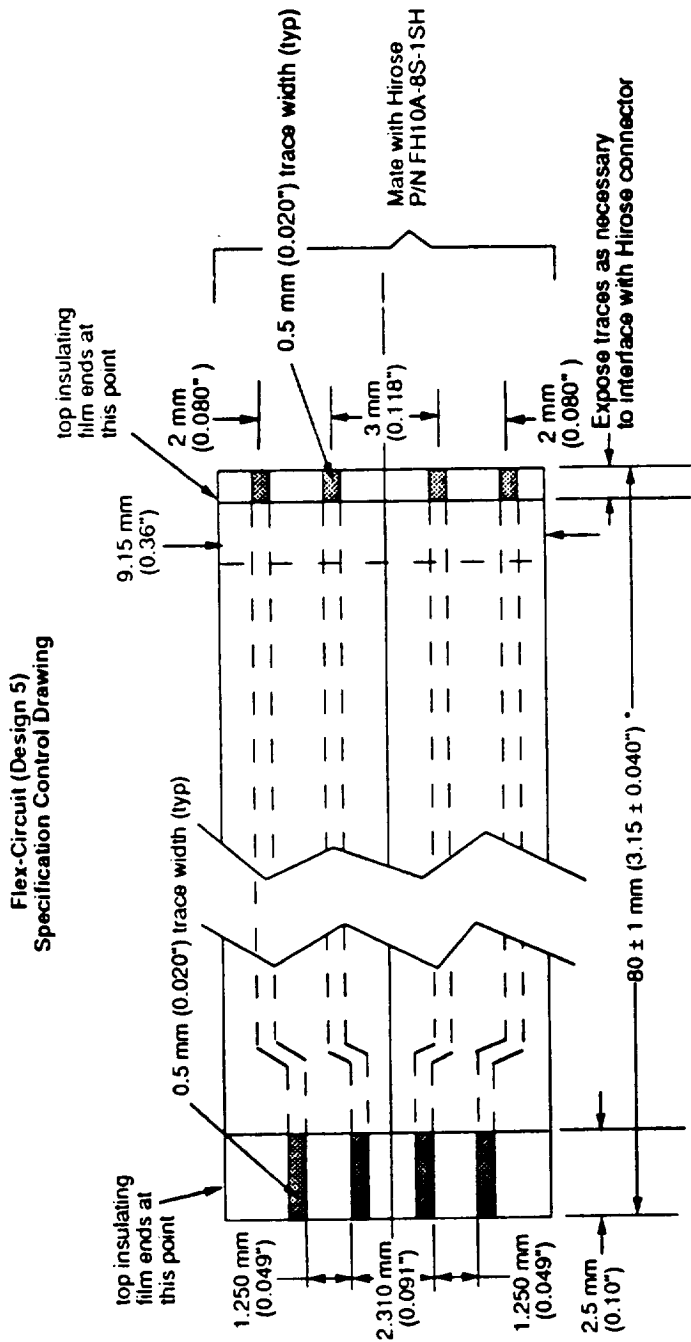
Flex-circuit Materials:

Base Insulating film: LARC-SI (Polyimide), 0.002 thick
Trace material: 200 Å Nickel tie-down layer with 1 oz. copper top coating
Top Insulating film: LARC-SI (Polyimide), <0.0005" thick
Stiffener material: Mylar
Stiffener adhesive: Mactac

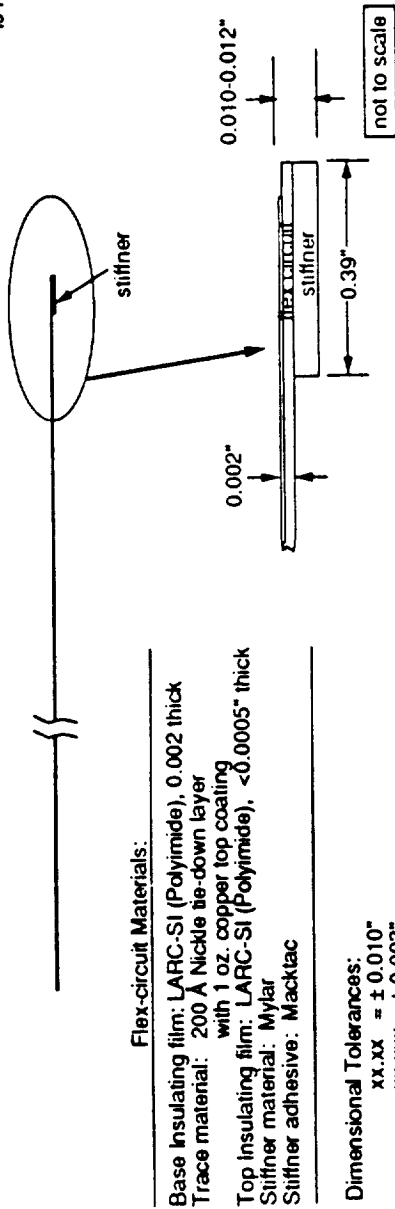
Dimensional Tolerances:
xx.xx = ± 0.010"
xx.xxx = ± 0.003"
Unless stated otherwise.

WGR/GTRI
1 May 97

Figure 7.3-1 Early version of flex circuit for use with position sensor circuit.



Note: (*) Indicates that length dimension is not to scale in this drawing.



WGR/GTRI
4 May 97

Figure 7.3-2 Simplified flex circuit design for coil pair die requiring only four traces.

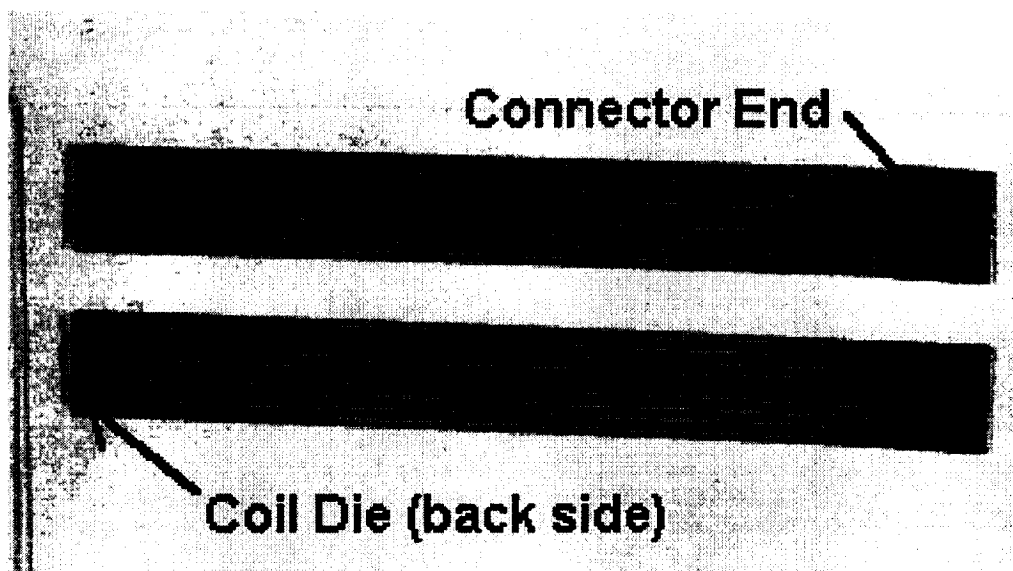


Figure 7.3-3 Flex circuit for use with coil pair die.

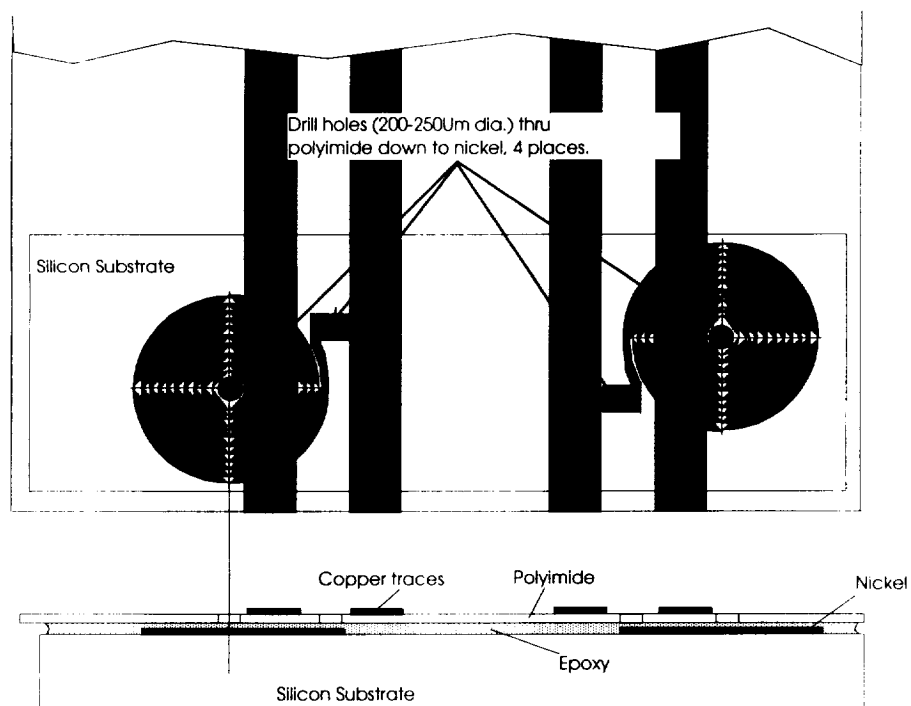


Figure 7.4-1 Coil pair packaging concept.

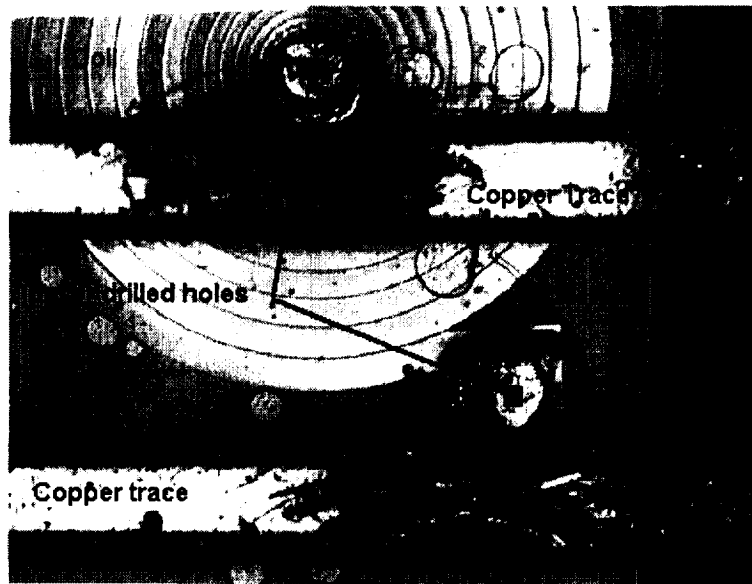


Figure 7.4-2 Coil pair assembly prior to making conductive interconnect between trace and coil.

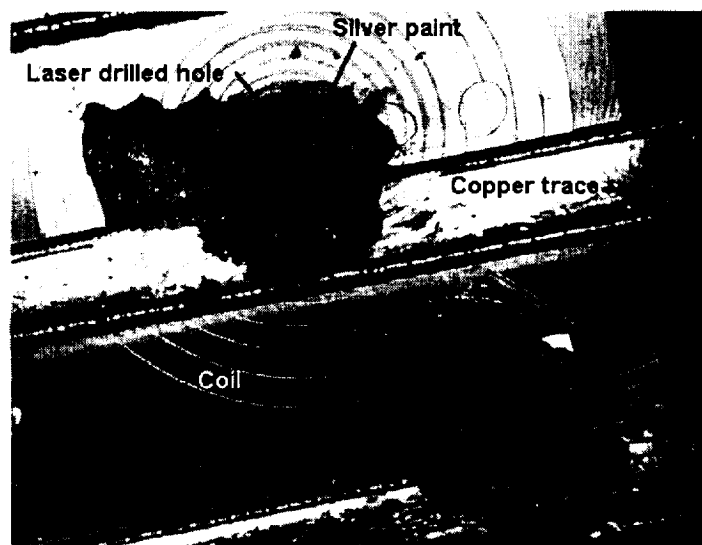


Figure 7.4-3 Conductive silver paint applied between coil and flex circuit trace.

7.5 Adhesive Selection.

The packaging design, shown in the previous section, requires two adhesive bonds. One bond is between the polyimide flex circuit and the nickel coils/silicon substrate. The other bond is between the back of the coil pair silicon substrate and the edge of the silicon mirror. These bonds need to have the following properties;

Flex Circuit-to-Coil Pair Substrate (Polyimide-to-Nickel/Silicon)

1. High enough tensile/shear strength so that the flex circuit does not pull off during installation and normal operation. This reflects more the adhesion properties of the adhesive rather than the strength of the bulk adhesive material.
2. Moderate cure time. The pot life should be long enough to allow time to position 5-10 flex circuits relative to the substrates, but once this is done you would like to be able to cure the assembly quick enough to allow a new batch of assemblies to be processed. A pot life of 1 hour and a cure time to 80% strength, with moderate heat, of 8-12 hours should be adequate.
3. Transparent enough to allow the coil pads to remain visible below the polyimide. This is needed so the laser drilling operator can locate the coil pads for drilling. Because the bond line is so small, this property is easily met with most adhesives considered.
4. Moderate thermal expansion. This is not a very important property for the SSD, but would be more important for space applications.
5. Moderate outgassing. Again, this is not a very important property for the SSD, but would be more important for space applications.

Coil Pair Substrate-to-Mirror (Silicon-to-Silicon)

1. High enough tensile/shear strength so that the coil pair assembly does not pull off during installation and normal operation. This reflects more the adhesion properties of the adhesive rather than the strength of the bulk adhesive material.
2. Moderate cure time. The pot life should be long enough to allow time to position 12 coil pair assemblies relative to the edge of a mirror segment, but once this is done you would like to be able to cure the assembly quick enough to allow a new batch of assemblies to be processed. A pot life of 1 hour and a cure time to 80% strength, with moderate heat, of 8-12 hours should be adequate.
3. Moderate thermal expansion. This parameter is important because this property, coupled with the flexibility of the bulk adhesive, will determine how much stress is transmitted to the mirror. Localized stress on the edge of mirror can cause serious deformation of the surface figure of the mirror with changes in temperature. No adhesive will have the low coefficient of thermal expansion of silicon, so the best that can be done is to try to pick an adhesive that can flex enough to minimize the stress transferred to the mirror.
4. Hardness. As stated in the previous paragraph, the adhesive should be flexible enough to minimize the stresses transmitted to the mirror. However, the adhesive can not be so flexible that it allows the coil pair substrate to move appreciably due to external mechanical, gravitational, and inertial forces received during operation. Motion of the coil pair substrate relative to the mirror will introduce position errors between adjacent mirrors and cause wavefront distortions.
5. Moderate outgassing. Again, this is not a very important property for the SSD, but would be more important for space applications.

In an attempt to satisfy the above criteria, several adhesive manufacturers were contacted and several people with experience in optical fabrication and assembly were contacted. After numerous conversations with adhesive manufacturers and fabrication/assembly experts, it was concluded that the best types of adhesives to test were two-part epoxies, one and two-part silicone (RTV) adhesives, and perhaps some of the cyanacrylate compounds. However, no measured data were found for the particular types of bonds needed for this assembly.

Without good test data pertaining to our bonding situation, tests were conducted on a number of adhesives. The tests were carried out using silicon dies the same size as the coil pair die, silicon wafer material the same as the mirrors, and LARC-SI flex circuits. The samples were prepared as shown in Figure 7.5-1 for testing of the two different bonds. After the samples cured, the two bonds were tested by either pulling the flex circuit relative to the die or pushing on the die relative to the mirror substrate, as shown in Figure 7.5-2. The results of these test are shown in the table of Figure 7.5-3.

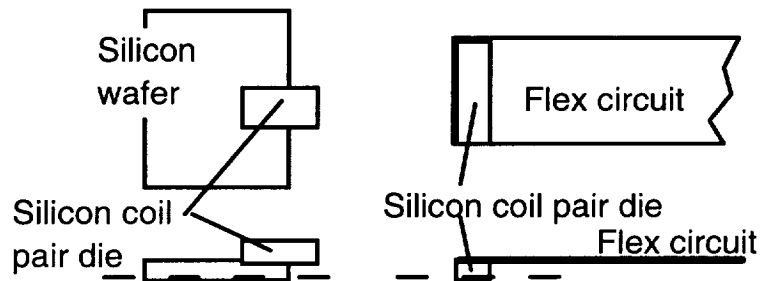


Figure 7.5-1 Preparation of samples for testing of adhesives.

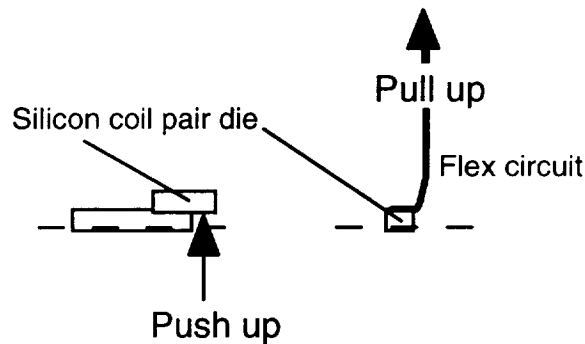


Figure 7.5-2 Pull testing of samples prepared using different adhesives.

Adhesive	Type	Bonding Components	
		Silicon to Silicon	Polyimide to Silicon
Devcon, 2-Ton, S-31	2 part Epoxy	Good	Poor
Devcon, 5 minute, S-205	2 part Epoxy	Good	Poor
Devcon, 5 minute gel, S-210	2 part Epoxy	Good	Fair
Ace, Plastic Bonder, #17394	2 part Epoxy	Poor	Good
3M, EC2216	2 part Epoxy	Good	Good
Pacer, Zap-A-Gap, PT-02	1 part Cyanoacrylate	Good	Poor
GE Silicone II	RTV	Good	Fair

Figure 7.5-3 Table showing the results of the adhesive pull tests

7.6 Fabrication of Coil Assemblies.

The procedure for fabrication and assembly of the prototype coil pair assemblies was straight forward and is given below;

1. Glue flex-circuit to coil-pair die. This is done under a microscope to insure proper alignment of the traces with the coil pads. For the prototype units assembled for the SSD, the die is initially mounted to a glass slide with lacquer, the adhesive is applied to the die, the flex circuit is placed over the die and positioned, the flex circuit is held in position with adhesive tape until the bond cures. For the SSD, batches of 15-20 units were assembled. For larger quantities a special fixture would be designed to make this process for time efficient.
2. Laser drilling of holes in polyimide film. After the adhesive has cured for a batch of the assemblies developed in Step 1, the batch is sent to a laser machining company for hole drilling. Holes are drilled through the polyimide down to the nickel pads on the coils. This operation is done by an operator visually (TV display) aligning the pads to a cross-hair on the display and then starting the machining sequence. The batch of coil pair die assemblies are mounted to an x-y motorized stage which the operator can move remotely. For the prototype assemblies required for the SSD, the die assemblies were moved manually by an operator. For larger quantities the special fixture mentioned in Step 1 would closely define the location of the dies and the die assemblies would be positioned under computer control, with an operator in the loop to observe the positioning and machining as a quality assurance measure. After the holes are drilled in the polyimide for a batch, the batch is returned to GTRI.
3. Connecting coils to traces. Upon receipt of a batch of die assemblies, the assemblies are cleaned and the traces are burnished slightly with a pencil eraser or burnishing tool used to clean contacts on electrical connectors. The traces adjacent to the holes are burnished to improve adherence of the silver paint to the traces. After burnishing the traces, conductive silver paint is applied between the traces and the nickel pads of the coil. These interconnects were shown earlier in Figure 7.4-3. The fresh silver paint conductors can be check immediately to insure conductivity. The die assemblies are allowed to dry and are then ready for assembly onto the mirrors. If extra protection is

required, the top of the silver paint/exposed trace region could be coated with a spray-on protective coating of polyimide or other suitable film.

The resulting coil pair assembly is relatively rugged, allows for a flexible interconnect between the mirror and printed circuit board, and provides an easy electrical interconnect at assembly. Because the SSD environmental requirements were so benign, no environmental testing was performed.

8.0 Conclusion.

The results of this study indicate that lightweight mirror structures can be produced using an EDM technique and magnetic coils/edge sensors can be packaged in a fashion that is consistent with the overall requirements of a lightweight tip-tilt mirror assembly. However, further development of the EDM fabrication process and procedures is required to make the technique usable for fabrication of optical components at costs competitive to other techniques. Also, further testing is required to determine the effects of the EDM process on substrate stresses that might cause problems during final figuring to during extreme temperature changes.

9.0 Recommendations.

If the problems encountered in this study can be solved a much improved product can be produced. A few of the problems that need to be addressed in any future work are;

For EDM mirror fabrication;

- a. Uniform electrical connection is required on the back of the substrate. This connection should be free of air and impervious to the dielectric fluid. Several ideas on how to accomplish this have been developed.
- b. An improved method of physically mounting the substrate to the aluminum rod is required. The new method must be mechanically strong, but must not grossly distort the substrate during machining, and must not scratch or mark the substrate surface. If an adhesive is used, it must cure or dry uniformly, must be removable with a solvent or moderate heat, and must be impervious to the dielectric fluid.
- c. A better understanding of the role of the dielectric fluid is needed and some performance tests of different fluids is required.
- d. Better flushing is required. This can be accomplished with better tool design.
- e. Cost analysis should be performed to determine optimum procedures for minimum production costs and maximum throughput.
- f. Environmental performance testing is required to verify optical performance under different environmental conditions of space.

For Sensor fabrication;

- a. Other position sensing techniques should be investigated.
- b. Improvements could be made in fixturing.
- c. More quantitative testing is needed for adhesives.
- d. Environmental performance testing is required to verify optical performance under different environmental conditions of space.
- e. Cost analysis should be performed to determine optimum procedures for minimum production costs and maximum throughput.

Addressing these problems should allow the completion of lightweight substrates suitable for SSD type applications or for any application requiring a lightweight optical element that can also be compatible with semi-conductor processes. A silicon optical/mechanical element allows for the development of an integrated structure that satisfies optical, mechanical, and electronic packaging requirements.

10.0 Acknowledgments:

The author would like to acknowledge the expertise and help supplied by Mr. Dennis Brown of the Georgia Tech machine shop in the fabrication and alignment of the EDM tool and operation of the EDM equipment. Dr. Michael Knotts is acknowledged for his help in developing some of the processes used in the initial study and his help in preparing the silicon mirror substrates for EDM machining. Stan Halpren used his expertise in dicing the sensor circuits and coil pairs and also in packaging the test circuits which required a considerable number of wire bonds. The author would also like to thank Sandy Montgomery, the NASA Marshall Program Manager; Greg Ames of Blue Line Engineering; John Karpinsky of SY Technologies; and Don Decker of Naval Air Warfare Center for their participation in technical discussions and helpful suggestions. And certainly, a great deal of thanks goes to NASA MSFC for the funding that allowed us to explore some of the technologies and processes described in this report.

Appendix A: Statement of Work

Statement of Work for Construction of Prototype Lightweight Mirrors

The following tasks describe the work necessary to fabricate eight (8) prototype lightweight mirror substrates and install position sensors on the edges of seven (7) of the mirror substrates.

1.0 Fabrication of lightweight mirror substrates.

- 1.1 Develop tooling, processes and procedures for producing lightweight silicon mirror substrates using electrical discharge machining (EDM) techniques.
- 1.2 Fabricate 8 lightweight silicon mirror substrates using EDM techniques.

2.0 Installation of position sensors on lightweight mirror substrates.

- 2.1 Cut position sensor dies from MOSIS into two circuit dies.
- 2.2 Cut coil dies from SY Technologies into individual dies.
- 2.3 Ship sensors and coils, produced in task 2.1 and 2.2, to SY Technologies
- 2.4 Develop position sensor chip packaging scheme
- 2.5 Analyze bonding requirements for sensor packaging and choose appropriate adhesives for the application.
- 2.6 Procure adhesives and application tools.
- 2.7 Test bonding adhesives, bonding process, and procedures.
- 2.8 Develop specifications for flex circuits for interface of position sensors to printed wiring board produced by BlueLine Engineering.
- 2.9 Develop fixtures for installation of position sensors and flex circuits onto segments.
- 2.10 Install position sensors and flex circuits onto segments.
- 2.11 Make wire bonds between sensors and flex circuits using wedge bonding technique.
- 2.12 Support electrical testing of the install sensor/flex-circuit.
- 2.13 Deliver seven (7) mirror substrates with sensors/flex-circuits and 1 spare mirror substrate without sensors/flex-circuits.

Appendix B: SSD Project Plan, Revision 2

DRAFT

ULTIMA
(Ultra Lightweight Telescope, Integrated Missions for Astronomy)
Segmented Corrector Research

Seven Segment Demonstrator
Project Plan

May 27, 1996

1.0 Introduction and Background

After a visit to PAMELA (Phased Array Mirror, Extendible Large Aperture) telescope demonstrator in the fall of 1994, the NASA administrator directed that the program emphasis be concentrated on space-based telescopes, and that applications in space-based astronomy be pursued with increased vigor. A science team was formed by the University of California, Berkeley, Space Science Laboratory proposed to the NASA Headquarters' Office of Space Sciences the development of an ISSA-based optical observatory using PAMELA derived technology. Although unsuccessful, a core group of proponents have coalesced to continue promoting the effort. Other involved parties include the Space Telescope Science Institute, the Jet Propulsion Laboratory, Langley Research Center, and several other universities and contractors. On March 23, 1995, the NASA associate administrator for the Office of Space Access and Technology directed the evolution of the technology from the laboratory to a space system. The Advanced Concepts Office was tasked with an effort focused toward defining a near term demonstration in space of the key technologies. A development plan was derived encompassing thin membrane mirrors as well as adaptive segmented mirror technologies. A strawman goal of a 20 meter filled aperture at the Earth-Sun L1 point was chosen as the strawman configuration for the ULTIMA (Ultra Lightweight , Integrated Missions for Astronomy).

Coincidentally, The Office of Space Science at NASA Headquarters began studying a potential follow-on to the Hubble Space Telescope. Eventually this effort was combined with a space interferometry program into the Origins Program. The HST follow-on is being called the Next Generation Space Telescope (NGST) and is initially conceived as an 8 meter filled aperture also operating at the Earth-Sun L1 point.

The following plan describes how OSAT-funded FY95 research efforts, SBIR projects, and MSFC discretionary funds are being combined in a project to make the next step in the maturation of active segmented space mirror technology which could be of benefit to ULTIMA, NGST, and other NASA advanced optics programs. The name chosen for this effort is the Seven Segment Demonstrator (SSD) project

2.0 Objectives, Requirements, and Scope

2.1 Management Objectives

The management objectives for the Seven Segment Demonstrator program are to demonstrate functionality and performance of a seven segment prototype array of hexagonal mirrors and supporting electromechanical equipment which addresses design issues critical to a space telescope.

2.2 Technology Requirements

The SSD will demonstrate technologies which will support these system capabilities:

- (1) to be transported in dense package to fit existing launcher payload envelopes, then construct/deploy to form space telescopes with large apertures,
- (2) to continually compensate for image distortions due to imperfections, natural disturbances, and equipment induced vibrations/deflections,
- (3) to provide very large primary reflectors of low mass and cost.
- (4) to develop the capability to correct spatial and temporal distortions typical of those arising from ambient space environments and from on-board system operations sufficiently to provide near diffraction limited performance,
- (5) to demonstrate the ability to form a segmented primary or quaternary mirror into a quasi-continuous surface with individual subapertures phased so that near diffraction limited performance is achieved, and
- (6) to demonstrate the feasibility of fabricating such systems with reduced mass and cost over alternate technologies.

The SSD program draws its resources from various sources and through various contract vehicles as shown in Figure 1. The project is enabled because MSFC is the lead center for all the constituent efforts (except the uncompensated contributions).

Seven Segment Demonstrator Project Team

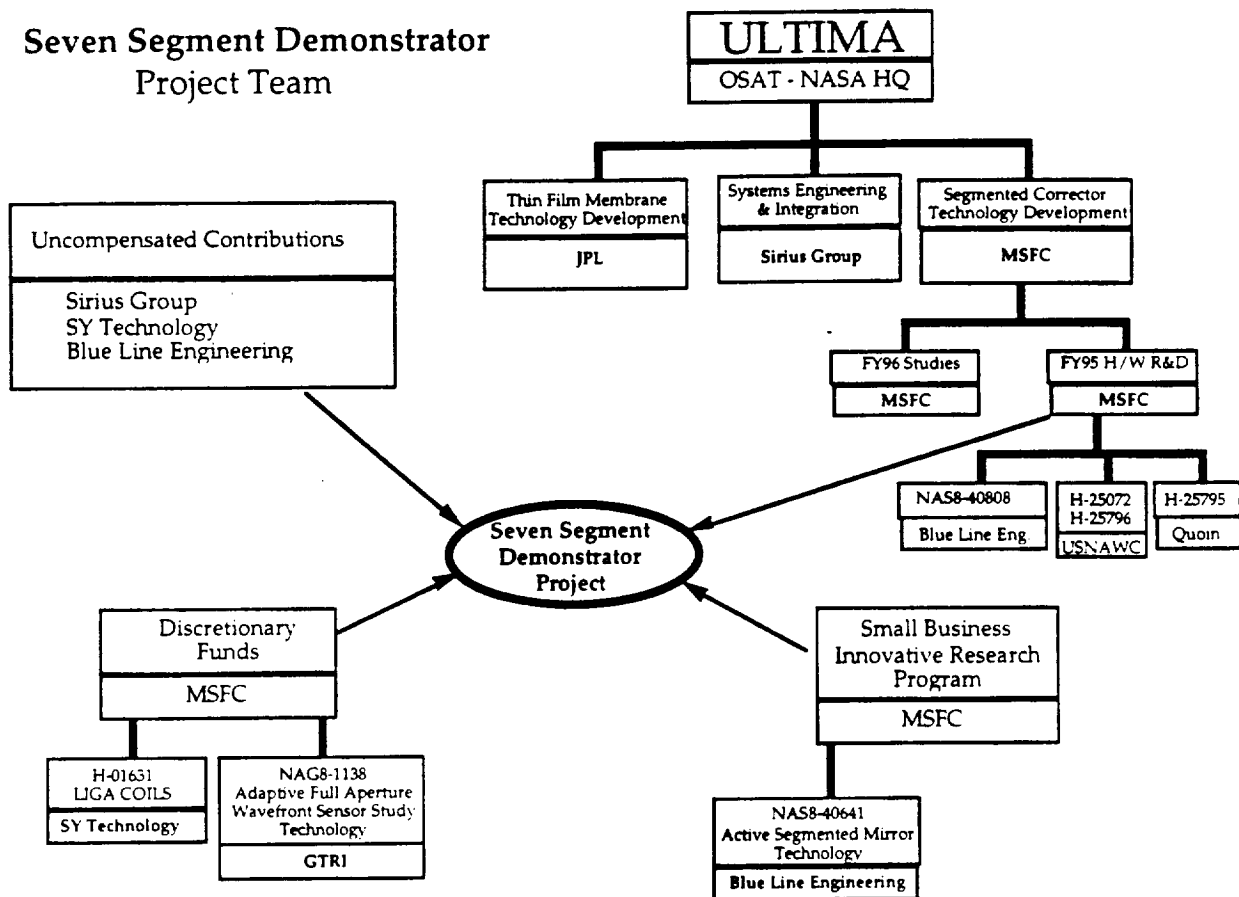


Figure 1. ULTIMA Project Team

2.2 Scope

The scope of the seven segment demo program spans concept development, prototype design, build, integrate, test, and demonstrate. Components of the seven segment demo are a precursor to constructing a much larger curved aperture made up of many more segments. It should demonstrate relevant technologies in:

- (1) Phase locking of a segmented mirror surface,
- (2) A compact phase loop controller capable of continuously phasing mirrors at a bandwidth in excess of 300 Hz,
- (3) A compact controller directly expandable to incorporate many more segments and a tip/tilt control loop for full wavefront correction,
- (4) Miniaturized, highly accurate edge sensors,
- (5) Miniaturized, highly accurate, lightweight actuators,
- (6) Very lightweight mirror faceplates,

- (7) Easy, reliable, robust construction/deployment methods and mechanisms, and
- (8) Cluster base for the array.

2.3 Guidelines/Assumptions

The following set of guidelines have been established to provide additional focus to the effort

- (1) The demonstrator will be designed for monochromatic operation at 632 nm, but is demonstrating a technology path to wavelengths in the range of $500 \text{ nm} < \lambda < 10 \text{ }\mu\text{m}$,
- (2) The main demonstration will be to set the SSD on a table, initialize the mirror segments to an out-of-phase and unaligned condition, then bring the flat mirror surface into a co-linear, phased condition, and then maintain that condition in the presence of disturbances provided by picking up the array and moving it to several orientations with respect to the local vertical and carefully striking the SSD to simulate impulsive disturbances.
- (3) The primary mirror array and segment surface figures will be flat.
- (4) The inter-segment gap spacing will be less than 2% of the aperture,
- (5) The regular hexagonal segment size will be 7 cm flat to flat,
- (6) The demonstrator will operate on 110V AC
- (7) SSD Hardware and software will deliverable property to MSFC. Deliverable s will be shipped to:
Transportation Officer, Building 4471
National Aeronautics and Space Administration
George C. Marshall Space Flight Center
Marshall Space Flight Center, AL 35812
- (8) There will be eight segments developed for the primary mirror. There array will consist of one center segment plus the first ring of six segments. The eighth segment is a fully completed spare. One segment to be located in the center of the array will have a circular hole in the middle.
- (9) A short assessment study will determine the optimum choice between testing an advanced algorithm controller with the seven segment array or a many segment simulator. Until the results are available, the baseline control algorithm for the seven segment array will be simple nearest neighbor. Controller electronics will be miniaturized to the largest extent possible
- (10) Edge sensor, actuator, and other data handling electronics will be miniaturized.
- (11) A "notebook" computer will serve as the top level host.
- (12) The baseline edge sensor technology will be the inductive device developed originally under SBIR by Kaman/Blue Line/SY Technology and lately improved by SY Technology. The fall back position is a simple capacitive gauge mounted beneath the faceplate.
- (13) A preliminary layout diagram for the test set-up is shown in figure 2.
- (14) It is desired to (A) retain design features for segment phasing, deployment mechanisms, fit, form, and function, of key optical, , and electronic components while (B) accepting design simplifications in place of highly polished mirrors, esoteric materials, NGST optical prescription, thermal management, plasma charging, and bus voltage in order to accomplish the project on time in budget.
- (15) Bandwidth of Controller will be 300 Hz.
- (16) Edge sensor and, if possible, actuator electronics reduced to application specific integrated circuits (ASICs).

Demonstration System Concept

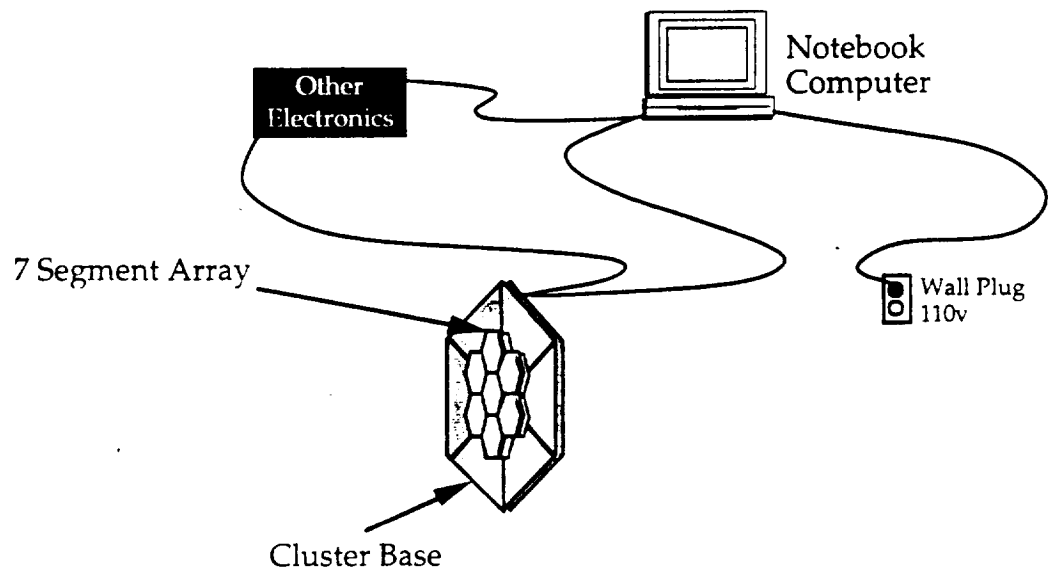


Figure 2. Layout for Demonstrator

3.0 Responsibilities and Interfaces

Roles and responsibilities and a discussion of the major interfaces is provided under bold heading for each participant in the team: MSFC, Blue Line Engineering, USNAWC, GTRI, and SY Technology. In addition, Dr. Glenn Zeiders and Dr. Harold Bennett will be working as general trouble-shooters and consultants for the project. Figure 3 illustrates those relationships.

Marshall Space Flight Center

At MSFC , Sandy Montgomery will be the project manager. He can be reached at (205) 544-1767. His fax number is (205) 544-5861. Henry Waites is the principle investigator over the PAMELA testbed. His phone number is (205) 544-1767. His fax number is (205) 544-5416.

3.1 Project Management

The lead organization for the Seven Segment Demonstrator Project will be Marshall Space Flight Center. Contracted activities of the project team member organizations will be through MSFC and the COTR for those activities is Sandy Montgomery. Periodic reviews to NASA headquarters and MSFC management will be given by MSFC to the management to minimize overhead in the project.

3.2.4.4 Test

As a minimum, MSFC will provide an optical bench in a clean stable environment, access to 110V power, and other basic amenities in support of configuring a test set-up. Subject to availability, MSFC will provide the WYCO 6000 interferometer, LCR meters , auxiliary cameras/monitors, and other auxiliary electrical, optical, and mechanical supporting hardware. MSFC will review the test procedures provided by Blue Line and identify the availability of test-specific government furnished equipment. MSFC will provide one man-level of support to Blue Line for two weeks to configure the SSD in the testbed and run tests. Data results will be analyzed by MSFC and Blue Line.

3.2.4.5 Demonstrations

MSFC will be responsible for developing and providing demonstration briefing materials. MSFC will organize, participate in, and possibly be the sole conductor of potential demonstrations at sites including MSFC, NASA headquarters, GSFC, JPL, and technical conferences and symposia in the United States.

Responsibilities & Interfaces

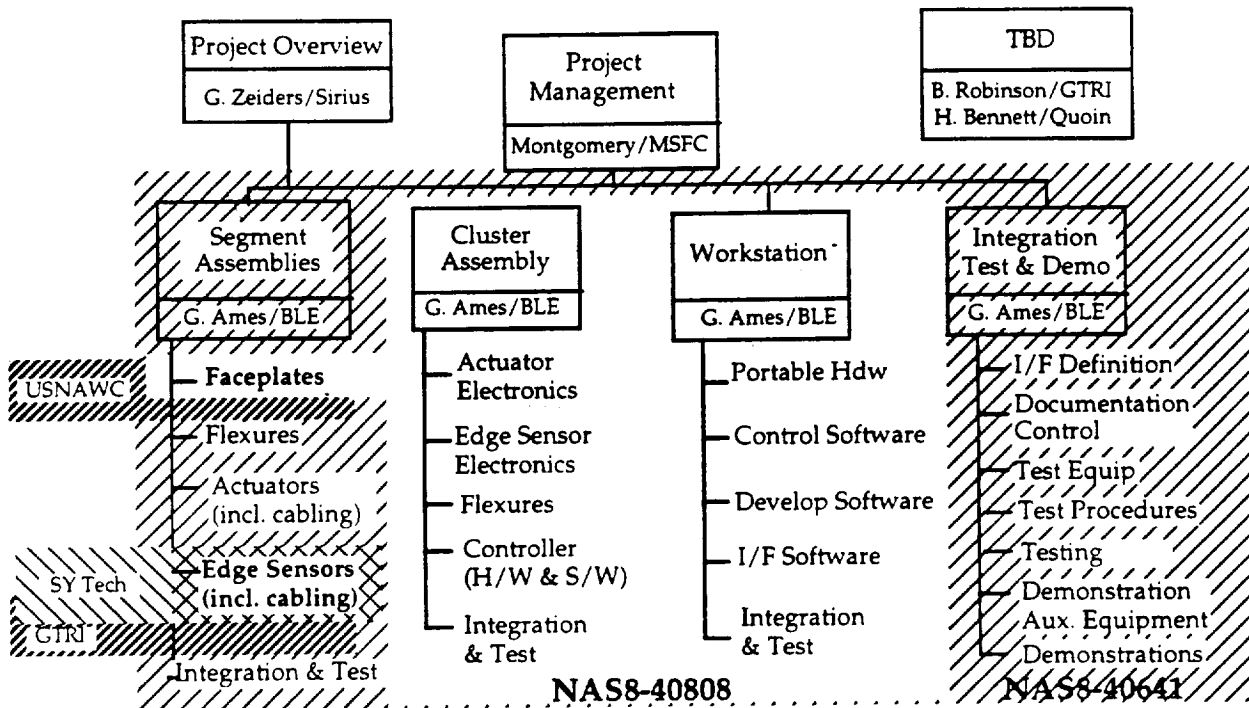


Figure 3. Management Structure

Blue Line Engineering

As shown in figure 3, Blue Line Engineering is responsible for the bulk of the activity. A major portion of the resources for the activity are available as a result of Blue Line's Phase II SBIR program to develop a seven segment demonstrator of 3 cm flat-to-flat size. The SSD elements are "early prototypes" toward the SBIR product. Because of this condition, intellectual property rights to the SSD segments are the same as for the those SBIR segments and must be accordingly protected by the government. Other privately-owned business members of the SSD team will be expected to execute Non-disclosure agreements with Blue Line. This situation does not supersede the intellectual property rights to the inductive sensor technology currently addressed in agreements between Kaman, Blue Line, and SY Technology.

Greg Ames is the lead engineer and project manager at Blue Line. He can be reached at (719) 447-1373. His fax number is (719) 389-0631. Specific responsibilities include:

3.2.1 Segment Assemblies

Blue Line will be responsible for the lead engineer function over all 3.2.4.X activities. Technical and programmatic issues will be identified and reported in a timely manner to NASA. Summary assessments will be given at the design reviews.

3.2.1.1 Faceplates

Blue Line will be responsible for deriving design specifications and delivering them to USNAWC for the eight faceplates.

3.2.1.2 Flexures

Blue Line will be responsible for design, fabrication, test and assembly of 21 flexures for the primary, 3 flexures for the spare mirror segment, and 3 spares for a total of 27 flexures.

3.2.1.3 Actuators

Blue Line will be responsible for design, fabrication, test and assembly of 21 actuators for the primary, 3 actuators for the spare mirror segment, and 3 spares for a total of 27 actuators.

3.2.1.4 Edge Sensors

Blue Line will assist in the development by providing design review comments on the miniaturized inductive edge sensors to GTRI and SY Technology. Blue Line developed alternate edge sensor technologies will be incorporated into the demonstrator (by Blue Line) at the discretion of Blue Line, i.e. no requirement is levied.

3.2.1.5 Integration & Test

Blue Line will be responsible for providing design coordination information during early stages of the program. Blue Line will receive and inspect edge sensor assemblies from SY Technology and finished and coated mirror faceplates from USNAWC. Blue Line will develop segment assembly procedures and tooling, Blue Line will plan, integrate, and execute appropriate functional tests for the segment assemblies. Blue Line will deliver segment assemblies for integration to the cluster assembly (3.2.2.5 below).

3.2.2 Lead Engineer for Cluster Assembly

Blue Line will be responsible for the lead engineer function over all 3.2.2.X activities. Technical and programmatic issues will be identified and reported in a timely manner to NASA. Summary assessments will be given at the design reviews.

3.2.2.1 Structure

Blue Line will be responsible for design, fabrication, test and assembly of the supporting structural element for the seven primary mirror segment assemblies(3.2.1.5). As much as possible, the cluster assembly should demonstrate desirable features of robust deployability, lightweighting, and low temperature operation.

3.2.2.2 Controller (H/W & S/W)

Blue Line will be responsible for developing the design of the central computational engine for the segment control algorithm and data management needed to receive error signals from (the wavefront error sensor system if one existed and) the segment edge sensors, interpret them and use the information to set piston commands for the segment actuators in a closed loop control system such that the array mirrors will be positioned to achieve the specified WFE and bandwidth. Blue Line will be responsible for the design, fabrication, test and assembly of the appropriate cluster-level hardware and software in this task.

Blue Line will be responsible for providing to GTRI the cluster-side interface definition necessary for GTRI to develop the cluster assembly-to-edge sensor electronics power and data interface hardware.

3.2.2.3 Actuator Electronics

Blue Line will be responsible for design, fabrication, test and assembly of 21 sets of actuator drive electronics for the primary, 3 sets for the spare mirror segment, and 3 spares sets for a total of 27 sets of actuator drive electronics. Reduction in size of the electronics will be a important design feature. Applications specific integrated circuits will be used wherever possible. Blue Line will trade-off locating the circuits on the segment or cluster assemblies, then implement the preferred approach.

3.2.2.4 Edge Sensor Electronics

Blue Line will be responsible for defining the optimum location and orientation of the edge sensors. SY Technology in conjunction with GTRI will develop the mounting and power and data interfaces for the edge sensor ASICs developed in conjunction with SY technology as part of an SBIR for NASA. If Blue Line develops alternate edge sensor technologies to be incorporated into the demonstrator, Blue Line will be responsible for design, fabrication, test and assembly of the appropriate number of primary and spare sets of edge sensor electronics.

3.2.2.5 Integration & Test

Blue Line will be responsible for providing design coordination information during early stages of the program. Blue Line will be in possession of the segment assemblies from 3.2.1 above, as well as the structure (3.2.2.1), cluster controller (3.2.2.2), actuator electronics (3.2.2.5), and possibly some Blue Line edge sensor components (3.2.2.4). Blue Line will develop cluster assembly procedures and tooling, Blue Line will plan, integrate, and execute appropriate functional tests for the cluster assembly. Blue Line will deliver the cluster assembly for system integration (3.2.4.3 below).

3.2.3 Workstation

Blue Line will be responsible for the lead engineer function over all 3.2.3.X activities. Technical and programmatic issues will be identified and reported in a timely manner to NASA. Summary assessments will be given at the design reviews.

3.2.3.1 Portable Computer

Blue Line will be responsible for developing the design of the central computational engine for the segment control algorithm and data management needed to receive error signals from (the wavefront error sensor system if one existed and) the segment edge sensors, interpret them and use the information to set piston commands for the segment actuators in a closed loop control system such that the array mirrors will be positioned to achieve the specified WFE and bandwidth. Blue Line will be responsible for the design, fabrication, test and assembly of the appropriate workstation-level hardware in this task.

A goal for this effort is for implementation in a single notebook-size computer.

3.2.3.2 Control Software

Blue Line will be responsible for developing the design of the central computational engine for the segment control algorithm and data management needed to receive error signals from (the wavefront error sensor system if one existed and) the segment edge sensors, interpret them and use the information to set piston commands for the segment actuators in a closed loop control system such that the array mirrors will be positioned to achieve the specified WFE and bandwidth. Blue Line will be responsible for the design, fabrication, test and assembly of the appropriate workstation-level software in this task.

A goal for this effort is for implementation in a single notebook-size computer.

3.2.3.3 Development Software

Blue Line will develop the necessary software tools required to accomplish tasks 3.3.3.2, 4, and 5 for the workstation and 3.2.2.2 for the cluster level controller.

3.2.3.4 Interface Software

Blue Line will be responsible for the development of user interface and telemetry software.

3.2.3.5 Integration & Test

Blue Line will be responsible for providing design coordination information during early stages of the program. Blue Line will be in possession of the cluster controller from 3.2.2.2, the workstation hardware from 3.2.3.1, the control software from 3.3.3.2 and the interface software from 3.2.3.4 and using the development software as needed, will develop workstation assembly procedures and tooling. Blue Line will integrate the workstation, and plan and execute appropriate functional tests for the workstation. Blue Line will deliver the workstation for system integration (3.2.4.3 below).

3.2.4 Integration, Test, & Demonstration

Blue Line will be responsible for the lead engineer function over all 3.2.4.X activities. Technical and programmatic issues will be identified and reported in a timely manner to NASA. Summary assessments will be given at the design reviews.

3.2.4.1 Configuration Control

Blue Line will be responsible for developing and maintaining a single, simple configuration management document. It will serve as the project definition of requirements specifications, and interface definitions. MSFC will provide distribution of periodic revisions.

3.2.4.2 Demonstration Auxiliary Equipment

Blue Line will be responsible for identifying, acquiring, and providing illumination sources, power supplies, cabling, reticles, pointing mounts, deployment drives and mechanisms, and any hardware or software item not included elsewhere, but required in support of a quality demonstration of the seven segment demonstrator. Blue line will also develop rugged, reusable containers transporting the demonstrator system between sights. The first use of the containers will be for deliver to MSFC of the integrated system for testing.

3.2.4.3 System Integration

Blue Line will be responsible for providing design coordination information during early stages of the program. Blue Line will be in possession of the cluster assembly from 3.2.2.5, the workstation from 3.2.3.5, and the demonstration auxiliary equipment from 3.2.4.2. Blue Line will develop system integration procedures and tooling. Blue Line will deliver the integrated system for test (3.2.4.4 below).

3.2.4.4 Test

Blue Line will be responsible for developing and providing specialized system performance test equipment and procedures and conducting the tests. MSFC will provide the PAMELA testbed as needed to support the tests. The appropriate integration/check-out tests (3.2.4.3) will be made at Blue Line then shipped in a rugged container (3.2.4.2) to MSFC. Blue Line then will work with MSFC for two weeks configure the array in the PAMELA testbed and run tests. Data results will be analyzed by Blue Line and NASA.

3.2.4.5 Demonstrations

Blue Line will be responsible for developing , and providing demonstration briefing materials. As far as possible, Blue Line will participate in and possibly be the sole conductor of potential demonstrations at sites including MSFC, NASA headquarters, GSFC, JPL, and technical conferences and symposia in the United States.

US Naval Air Warfare Center

At USNAWC , Don Decker will be the lead engineer and project manager. He can be reached at (619) 939-3247. His fax number is (619) 939-6593.

3.2.1.1 Hexagonal Mirror Fabrication

Blue Line Engineering will provide to USNAWC basic design specifications for the hexagonal mirror faceplates. USNAWC will receive requirements for feedthrough or attach point accommodations in the faceplate from SY Technology and be responsible for incorporating appropriate features in the faceplate design. USNAWC will be responsible for interfacing with Blue Line Engineering to incorporate interface design features for the actuator flexures. USNAWC will be responsible for design, fabrication, coating, finishing, and assembly(if required) of eight faceplates. The eight faceplates will include six outer ring segments, one inner ring segment, and one spare for an outer ring segment. USNAWC is responsible for fabricating the central segment with the required central hole.

3.2.1.5 Integration & Test

USNAWC will be responsible for testing the completed mirror segments to determine optical figure quality. The faceplates will be non-destructively marked as an identification key for the test results. The test result will be published and provided to Blue Line Engineering and MSFC. USNAWC will be responsible for packaging and delivering the eight completed faceplates to Blue Line for integration with the other segment assembly components.

3.2.4.5 Demonstrations

USNAWC will be responsible for developing and providing demonstration briefing materials. As far as possible, USNAWC will participate in potential demonstrations at sites including MSFC, NASA headquarters, GSFC, JPL, and technical conferences and symposia in the United States.

Georgia Tech Research Institute

At GTRI, Bill Robinson will be the lead engineer and project manager. He can be reached at (404) 894-3646. His fax number is (404) 894-5073.

3.2.1.1 Faceplates

GTRI Line will be responsible for design, fabrication, and test of power and data interfaces between the edge sensor/edge sensor electronics package and the cluster assembly. GTRI will work with SY Technology to determine the sensor-side interfaces and Blue Line Engineering and USNAWC to develop the segment and cluster-side interfaces. GTRI will deliver to SY Technology the interface hardware for integration with other edge sensor components by SY Technology.

3.2.2.4 Edge Sensor Electronics

GTRI will be responsible for fabricating edge sensor electronics ASIC per the instructions provided by SY Technology. GTRI will deliver the ASICS to SY Technology for integration with the LIGA coils and other edge sensor components.

3.2.4.5 Demonstrations

GTRI will be responsible for developing and providing demonstration briefing materials. As far as possible, GTRI will participate in potential demonstrations at sites including MSFC, NASA headquarters, GSFC, JPL, and technical conferences and symposia in the United States.

SY Technology

At SY Technology, Rod Clark will be the project manager. He can be reached at (205) 544-1767. His fax number is (205) 544-5861. John Karpinsky will be the lead engineer. He can be reached at (205) 722-9095. Their fax number is (205) 722-9097.

3.2.1.1 Faceplates

GTRI Line will be responsible for design, fabrication, and test of power and data interfaces between the edge sensor/edge sensor electronics package and the cluster assembly. SY Technology will be responsible for providing to GTRI a definition of the sensor-side interfaces. Blue Line will be responsible for providing the cluster assembly-side power and data interfaces. SY Technology will be responsible for providing to USNAWC requirements for feedthrough or attach point accommodations in the faceplate.

3.2.1.4 Edge Sensors

SY Technology will design, fabricate, and test primary and spare LIGA fabricated inductor coils for the edge sensor assemblies

3.2.2.4 Edge Sensor Electronics

SY Technology will design, fabricate, and test primary and spare edge sensor electronics ASICs.

3.2.1.5 Integration & Test

SY Technology will be responsible for integrating the edge sensors (3.2.1.4), the GTRI-provided edge sensor electronics ASICs (3.2.2.4) and the GTRI-provided power and data interface hardware (3.2.1.1) and testing the completed edge sensor assemblies. The edge sensors will be non-destructively marked as an identification key for the test results. The test results will be published and provided to Blue Line Engineering and MSFC. SY Technology will be responsible for packaging and delivering the completed sensor assemblies to Blue Line for integration with the other segment assembly components.

3.2.4.5 Demonstrations

SY Technology will be responsible for developing and providing demonstration briefing materials. As far as possible, SY Technology will participate in potential demonstrations at sites including MSFC, NASA headquarters, GSFC, JPL, and technical conferences and symposia in the United States.

4.0 Programmatic and Schedule

4.1 Project Approach

The FY95 effort (which will actually occur in FY96) prepares for the fabrication of a several hundred segment, half-meter ground telescope next year, by pioneering the design with a seven segment bench demonstrator array this year. A classic design review process will be pursued which has four major milestones:

Requirements Review - Assess completeness of project level & system requirements, assignment of roles and responsibilities, and organizational commitments. The publication of this document will serve in place of the requirements review.

Preliminary Design Review- held to demonstrate preliminary designs meet system requirements, all interfaces and verification methodologies are identified. Successful completion of PDR will result in approval of configuration item specifications, release of the preliminary design drawings, and serve as prerequisite to proceeding with detailed design.

Critical Design Review - all technical problems and design anomalies must be resolved without comprising system performance, reliability, and safety before CDR. Successful completion will result in the release of approved drawings for fabrication, approval of manufacturing plan, test plan and procedures, and permission to proceed with the software coding and system qualification testing and integration.

System Test- Conduct of planned test program. Successful completion will result in the publication of a system description and performance assessment briefing materials.

Although some subsystems and components will have a unique development path, the development of the overall project shall proceed along the following

Milestone Schedule

Wednesday	11/1/95 Start Trade studies derive system concepts/requirements
Monday	5/6/96 Requirements Review (RR)
Thursday	5/9/96 Regular Telecon
Thursday	5/23/96 Regular Telecon
Monday	5/30/96 Preliminary Design Review (PDR) - 2 days(30&31)
Thursday	6/6/96 Regular Telecon
Tuesday	6/14/96 Release PDR Drawings. Begin working toward CDR
Thursday	6/20/96 Regular Telecon
Holiday	7/4/96 4th of July - no telecon
Thursday	7/11/96 Regular Telecon
Thursday	7/25/96 Regular Telecon
Thursday	8/8/96 Critical Design Review (CDR) - 2 days(8&9)
Thursday	8/22/96 Regular Telecon
Thursday	9/5/96 Regular Telecon
Monday	9/13/96 Release Final Drawings. Begin Fabrication.
Thursday	9/19/96 Regular Telecon
Thursday	10/3/96 Regular Telecon
Friday	10/4/96 Faceplates Shipped to Blue Line
Friday	10/4/96 segment assembly fixtures and flexures ready
Tuesday	10/10/96 Flexures + actuators bonded to face plate
Friday	10/11/96 Edge Sensor Assemblies shipped to Blue Line
Thursday	10/17/96 Regular Telecon
Friday	10/18/96 cluster parts available:controller, structure, act. electronics, etc.
Monday	10/25/96 Complete Segment Assemblies/Check-out
Monday	10/25/96 Begin cluster assembly
Thursday	10/31/96 Regular Telecon
Thursday	11/7/96 Aux. Demo components available
Monday	11/13/96 Complete Cluster assembly/check-out
Monday	11/13/96 Begin system integration
Thursday	11/14/96 Regular Telecon
Monday	11/28/96 System Integrated. Begin preparing briefings. Ship to MSFC
Thursday	11/28/96 Regular Telecon
Monday	12/12/96 System Tests complete
Wednesday	12/19/96 First Demonstration at NASA Headquarters

4.2 Meetings and Workshops

Regular meetings and workshops will be conducted as needed to effectively administer the program, to encourage technical interchange among the participants, and to reach and inform potential suppliers/manufacturers segments. To the largest extent feasible, this will be done by teleconference and videoconference to reduce costs. Key individuals will be expected to travel to MSFC for presenting their respective portions of the Major reviews.

4.4 Schedule

Activities will begin ASAP and proceed at least thru the end of calendar year 1996 with expectation for some more demonstrations in 1996 or the duration of the contracts whichever comes first.

4.5 Ratification

Since this exercise in its entirety is not the subject of contractual agreements between the parties and/or the government, the responsibilities listed above do not represent legal obligations. In some areas of the endeavor, there are contracts in place which are legally binding. In such cases this document in no way supersedes those contracts.

The purpose of the following signatures is to indicate the undersigned (1) are informed on the basic nature of the project, (2) will accept the structure of the team and organization of the work, and (3) are committed to achieving the stated goals by making use of whatever reasonable and available resources can be brought to bear.

Edward E. Montgomery
Space Science & Applications Systems Office
George C. Marshall Space Flight Center

Gregory H. Ames
CEO, President
Blue Line Engineering Co.

Don L. Decker
Head, Advanced Optical Technology Section
US Naval Air Warfare Center

William G. Robinson
Senior Research Scientist, Electro-optics Lab
Georgia Tech Research Institute

Rod L. Clark
Director of Wave Optics
SY Technology, Inc.

Glenn W. Zeiders
President
Sirius Group

Harold E. Bennett
President
Bennett Optical Research

Appendix C: Specifications for Model SM-150B EDM Equipment

Machine Tool

Positioning table travel	6" x 8"	152 x 203mm
XY positioning, vernier	.0001"	.005mm
Worktable size	9" x 15"	229 x 381mm
Worktank size	13" x 20" x 9" deep	330 x 508 x 229mm deep
Platen-to-table distance	16" max	406mm max
Ram travel	6"	152mm
Infeed display, 1" dial indicator	.001"/div.	.01mm/div.
Automatic shutoff	Adjustable	
Platen size	5" x 13"	127 x 330mm
Maximum electrode weight	300 lb	136 kg

Power Supply

EDM controls	% On-time, frequency (.5-250KHz), gap spacing, arc-sensor, polarity, output power level
Maximum average current	1, 2, 5, 10, 15, 20-amp (40-amp optional)
Arc duration range	1.5 to 1800 microseconds
Servo controls	Auto, manual, dither, edge-finder, speed
Maximum stock removal rate (20-amp) (negative electrode) (positive electrode)	1.2 cu in/hr (graphite/steel) .5 cu in/hr (graphite/steel)

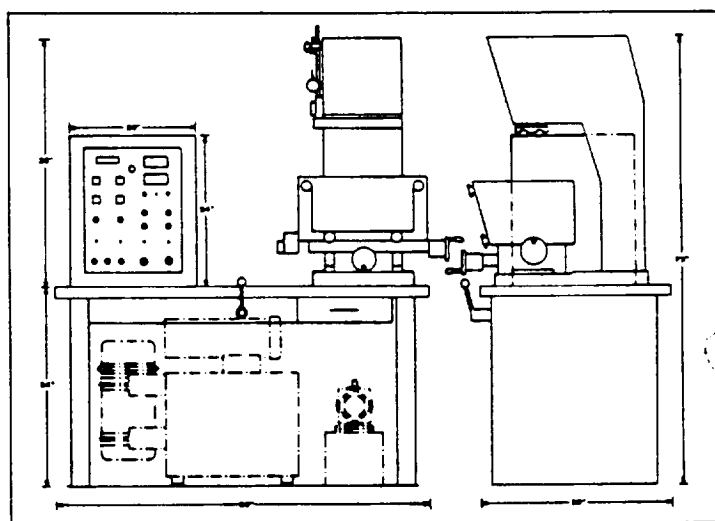
The 150B Power Supply can be retrofitted to older machine tools.

Dielectric System

Worktank capacity	9.4 gal	36 lit
Reservoir capacity	30 gal	114 lit
Flushing pressure, adjustable	0-50 psi	
Vacuum	0-15 in Hg	
Filtration, replaceable element	5 micron	

General

Height/width/depth	72" x 60" x 30"	1829 x 1524 x 762mm
Net weight	1350 lb	613 kg
Color	Machine tool grey	
Power input (standard) (optional)	105-125 vac, 60 Hz, 1 ph, 30-amp Other voltages and frequencies on request	



Hansvedt Engineering, Inc. reserves the right to discontinue products and to change product specifications at any time without obligation to incorporate new features in products previously sold.

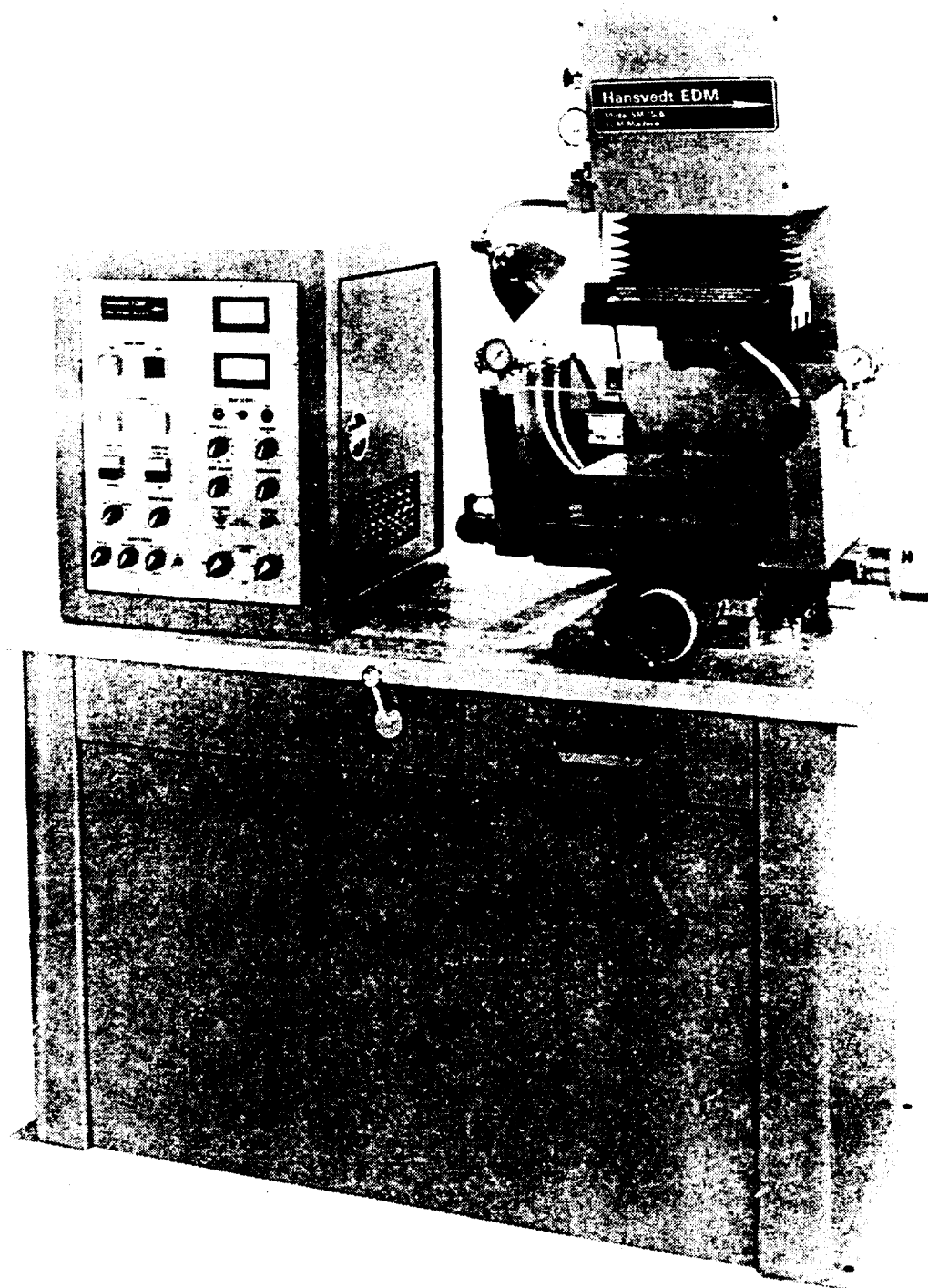


EDM DIVISION

Hansvedt Engineering, Inc., 3 Kettering Park, P.O. Box S, Urbana, Illinois 61801 U.S.A.
Phone (217) 384-5900. Cable: HANSVEDT, URBANA, IL (USA). Telex: 250131

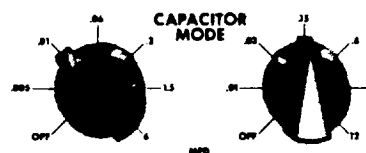
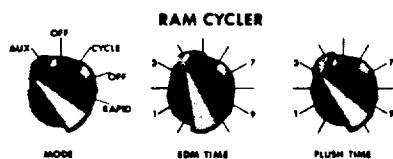
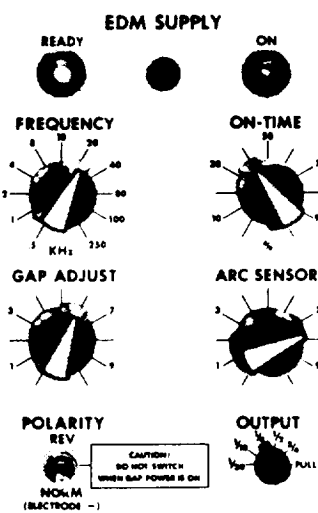
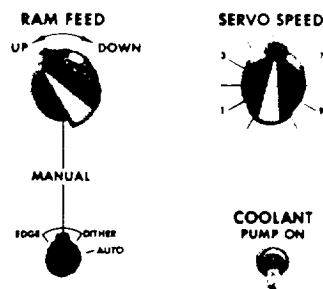
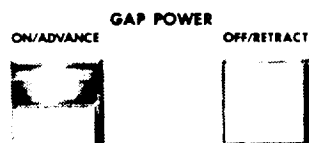
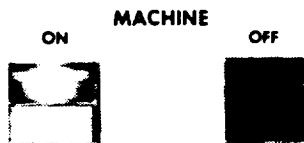
DISTRIBUTED BY

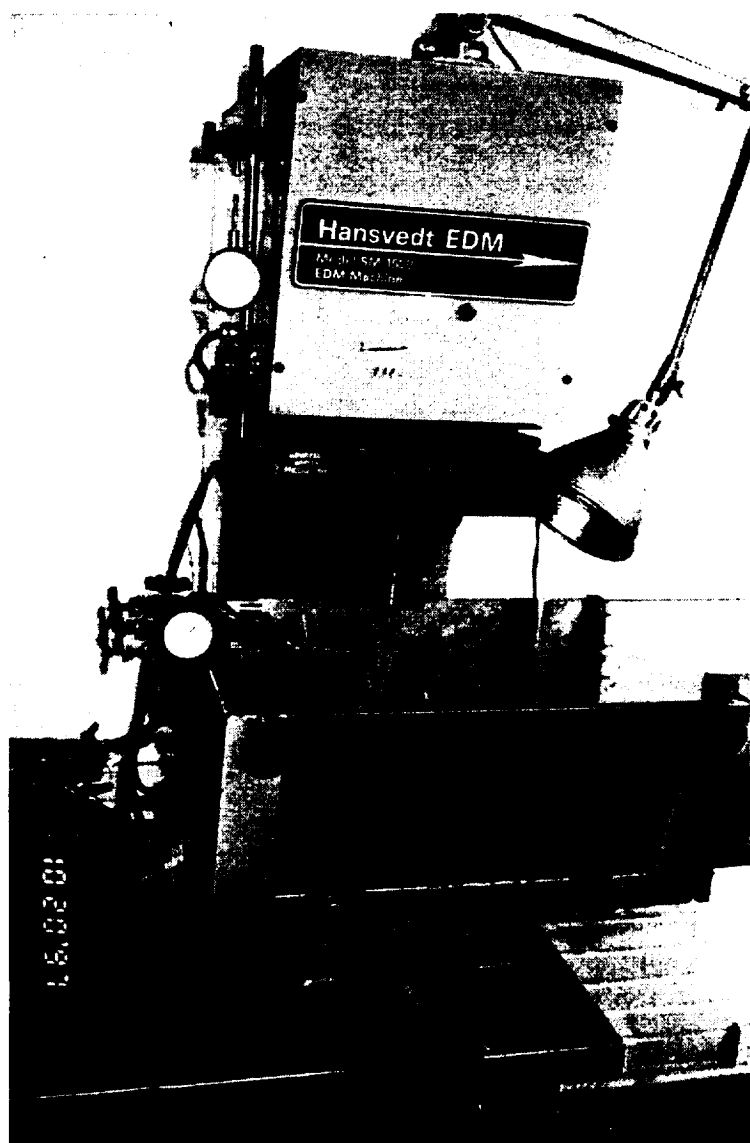




**HANSVEDT
MODEL SM-150B
EDM MACHINE**

Hansvedt EDM
150B Power Supply







REPORT DOCUMENTATION PAGE

FORM APPROVED
OMB No. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of the collection of information, including suggestions for reducing the burden to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302 and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503

1. AGENCY USE ONLY (Leave blank)		2. REPORT DATE 1 DEC 97	3. REPORT TYPE AND DATES COVERED FINAL (10 DEC 96 - 10 SEP 97)	
4. TITLE AND SUBTITLE OF REPORT CONSTRUCTION OF PROTOTYPE LIGHTWEIGHT MIRRORS			5. FUNDING NUMBERS CONTRACT NO. H-27657D	
6. AUTHOR(S) WILLIAM G. ROBINSON				
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) ELECTRO-OPTICS, ENVIRONMENT, AND MATERIALS LAB. GEORGIA TECH RESEARCH INSTITUTE GEORGIA INSTITUTE OF TECHNOLOGY ATLANTA, GEORGIA 30332			8. PERFORMING ORGANIZATION REPORT NUMBER: NOT APPLICABLE	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) NASA / MSFC ATTN: (PS02) MARSHALL SPACE FLIGHT CENTER, AL 35812			10. SPONSORING/MONITORING AGENCY REPORT NUMBER: NOT APPLICABLE	
11. SUPPLEMENTARY NOTES:				
12a. DISTRIBUTION AVAILABILITY STATEMENT NO LIMITATIONS			12b. DISTRIBUTION CODE _____	
13. ABSTRACT (Maximum 200 words)				
14. SUBJECT TERMS LIGHTWEIGHT MIRRORS, ELECTRICAL DISCHARGE MACHINING, EDM, POSITION SENSORS, OPTO-MECHANICAL PACKAGING			15. NUMBER OF PAGES: 61	
			16. PRICE CODE _____	
17. SECURITY CLASSIFICATION OF REPORT: UNCLASSIFIED	18. SECURITY CLASSIFICATION OF THIS PAGE UNCLASSIFIED	19. SECURITY CLASSIFICATION OF ABSTRACT UNCLASSIFIED	20. LIMITATION OF ABSTRACT NONE (UL)	